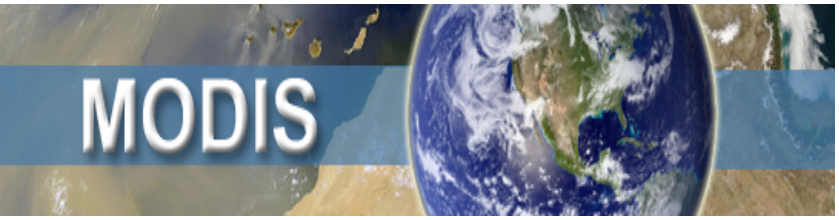
Creating a global aerosol data time series from MODIS, VIIRS and beyond



Robert C. Levy (NASA-GSFC)
robert.c.levy@nasa.gov

Shana Mattoo, Leigh Munchak and Richard Kleidman (SSAI/GSFC)
Lorraine Remer (UMBC/JCET), Falguni Patadia (GESTAR/GSFC),
Robert Holz (SSEC/UWisc), and others

Presented to CERES meeting - 6 May 2015 @ NASA-LaRC – Thank you Norm Loeb

aerosols in the climate system

- Understanding climate requires accurate and complete aerosol characterization
- … which requires accurate and complete global aerosol data
- … which requires global observations.
- … which requires high quality techniques to retrieve aerosol properties
- … which requires accurate global measurements
- … which requires detailed characterization of the sensors and algorithms being used

- Just note, that we also want to monitor air quality, so another audience

Aerosol Climate Data Records (CDRs)?

"A time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change."

Some requirements

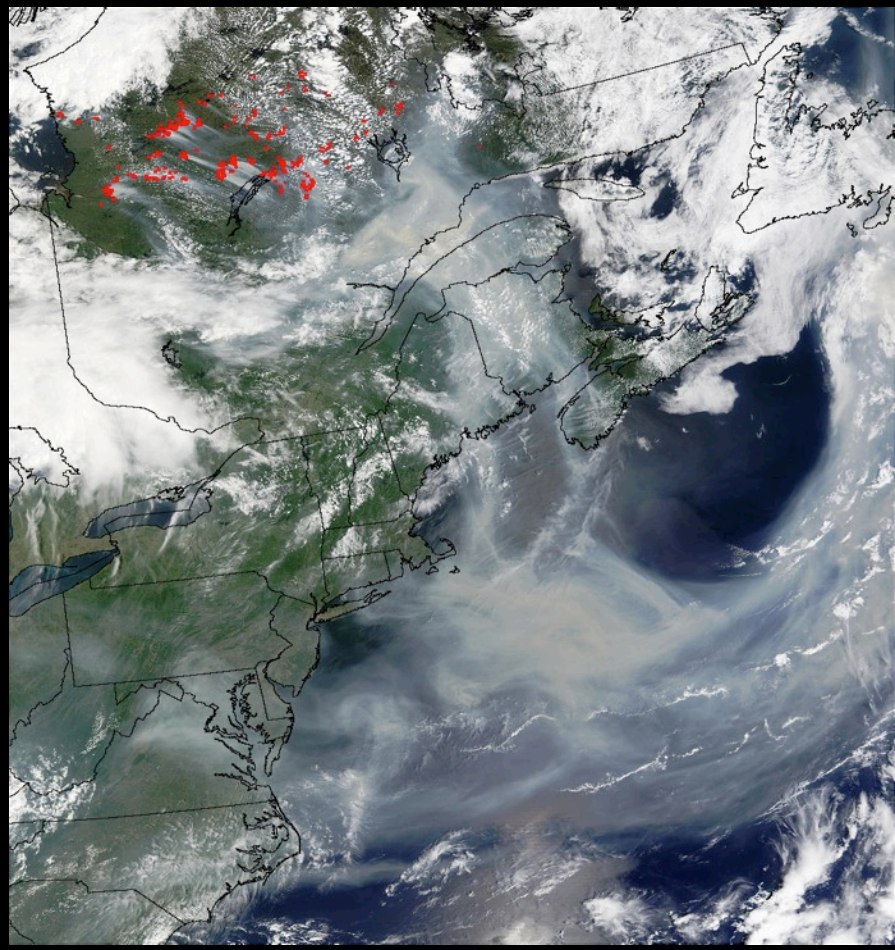
- Measurements sustained over decades
- Measurement of measurement performance (e.g. calibration, stability)
- Acquired from multiple sensors / datasets

MODIS is 15+ years, how do we extend across decades?

Outline

1. Introductionary stuff
2. MODIS Collection 6 updates (algorithm wise)
    1. DT ocean
    2. DT land
3. Terra vs Aqua (and calibration and trends)
4. Onward to S-NPP VIIRS and climate data records?
5. Summary, challenges, etc

Haze and Smoke from space

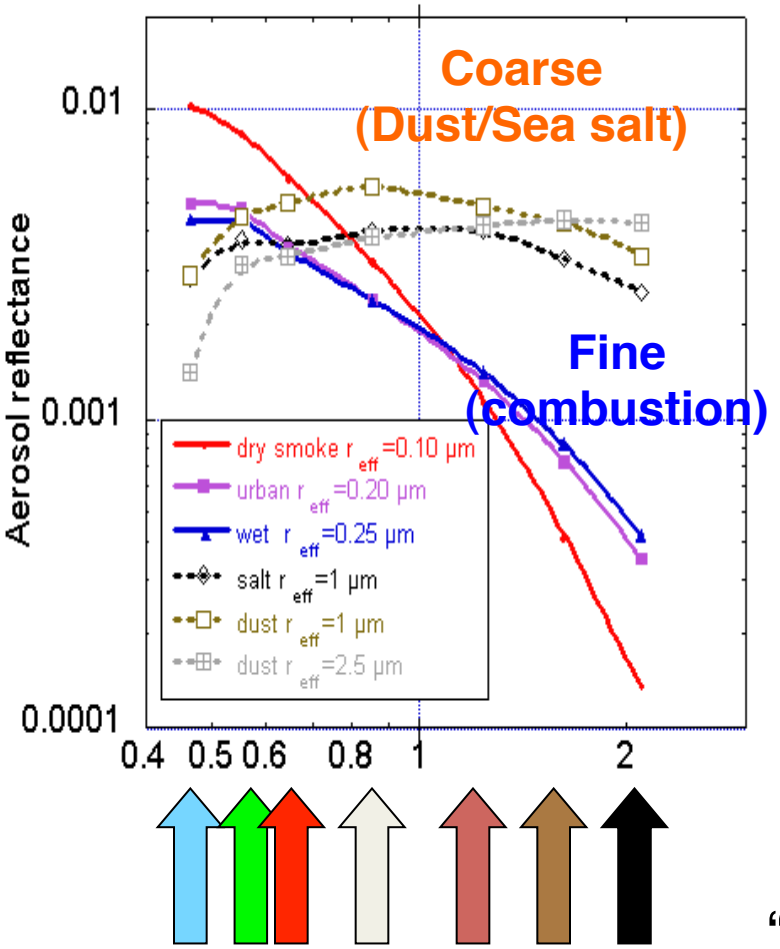


Haze over the Ganges/Bay of Bengal (4 December 2001)

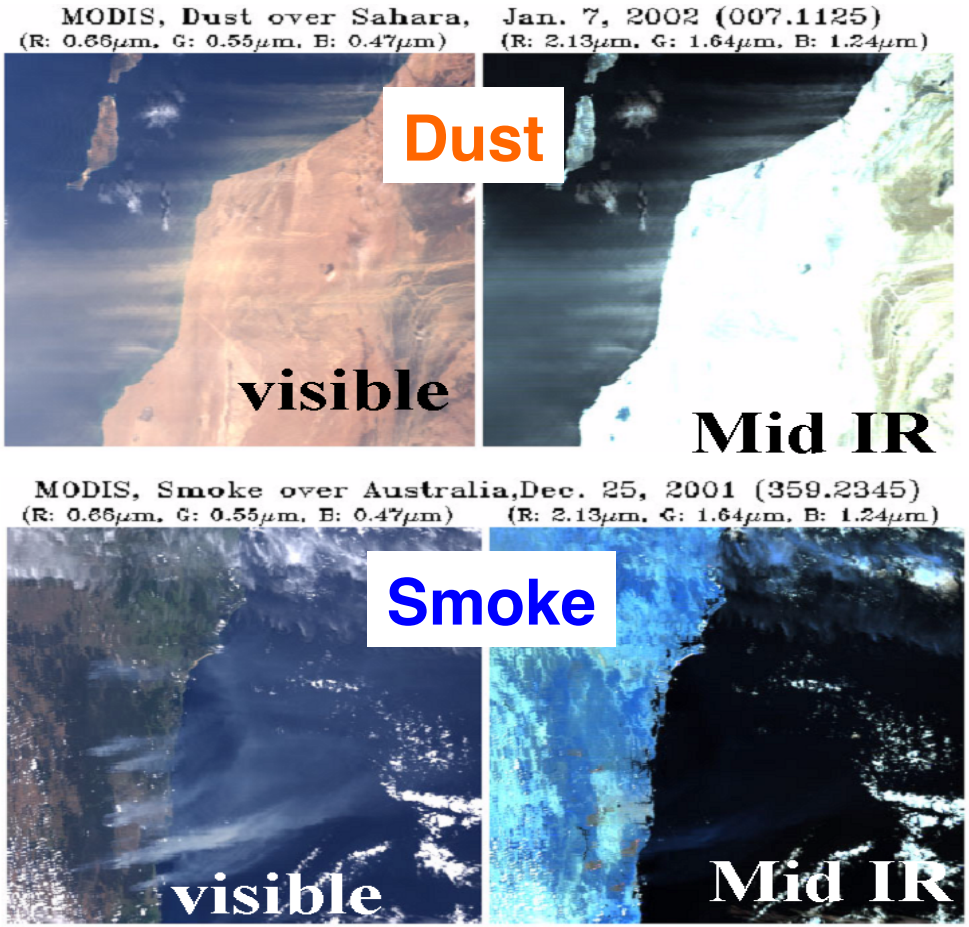
Smoke transported over Eastern Canada/USA (8 July 2002)

http://earthobservatory.nasa.gov/

Aerosol reflectance (and AOD) has spectral dependence (AE)
(.. and AE is dependent on aerosol size)



MODIS "Channels"

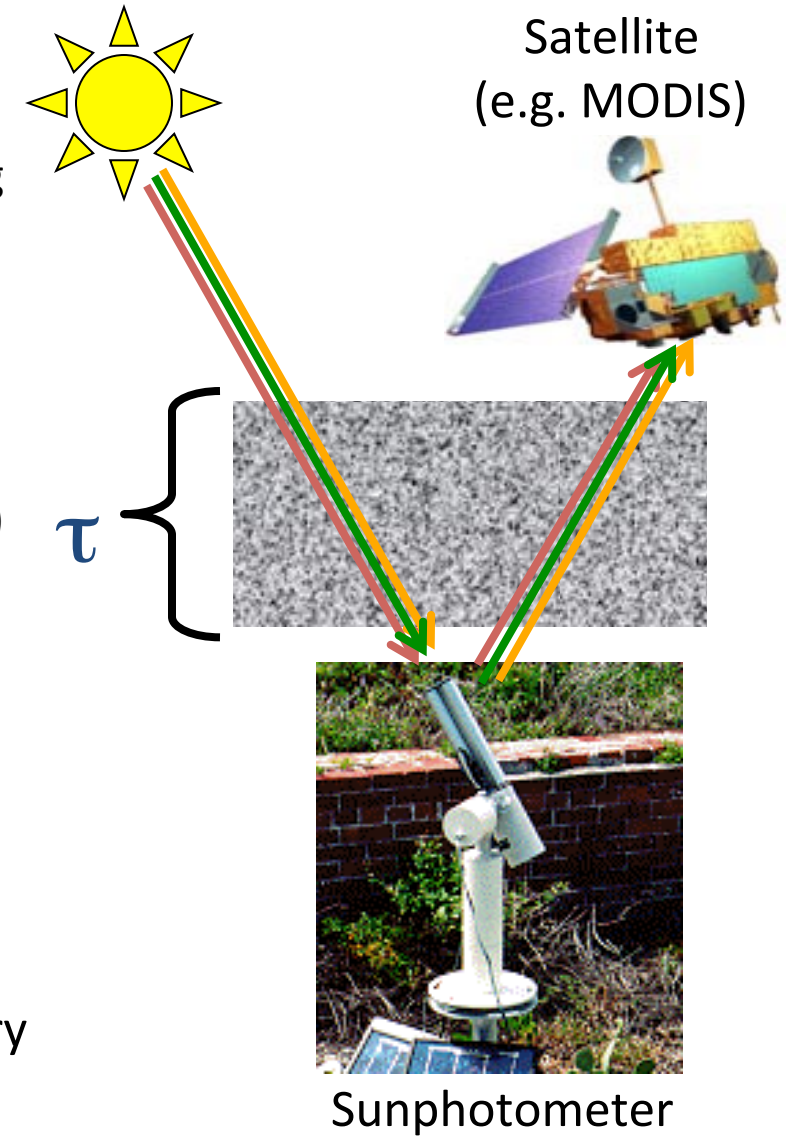


"Big" particles (e.g. Dust) reflect in SWIR
"Small" particles (smoke/pollution) do not.

Y. Kaufman, D. Tanré

Passive Remote Sensing of AOD

- Steps to observing aerosol properties
  - Measure spectral light extinction/scattering
  - Separate the aerosol signal from the total,
  - Retrieve aerosol optical properties
  - Infer aerosol physical properties (size, type)
- FROM THE GROUND (SUNPHOTOMETER)
  - Ground reflectance negligible
  - Extinction: directly relates to AOD
- FROM SPACE (SATELLITE)
  - Ground reflectance NOT negligible
  - Scattering: more assumptions necessary



MODIS
Moderate resolution Imaging Spectroradiometer

Orbit: 705 km, sun-synchronous, over same point every 16 days
Equator crossing: 10:30 (**Terra**, since 2000), 13:30 (**Aqua**, since 2002)

Swath: 2330 km (55° cross track)

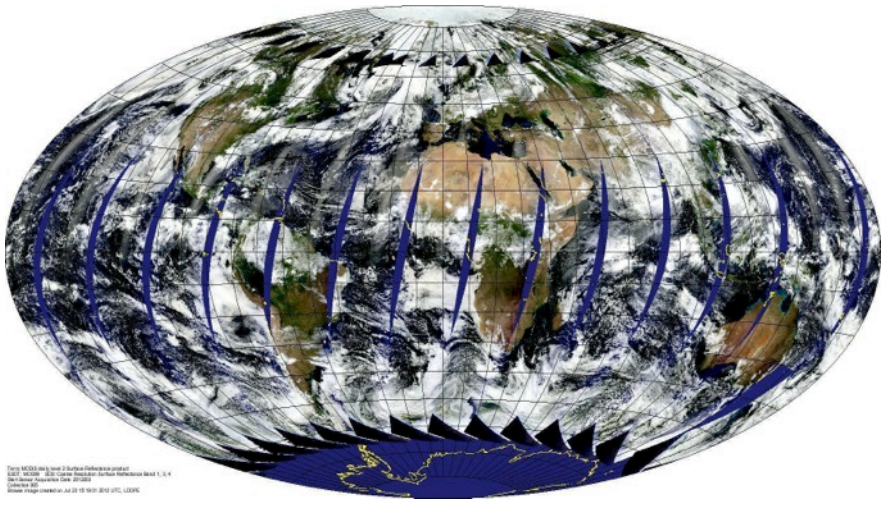
Spectral Range: 0.4-14.4μm (36 bands). 19 in solar spectrum (< 4.0 μm)

Spatial Resolution: 250m (2 bands) 500m (5 bands) 1000m (29 bands)

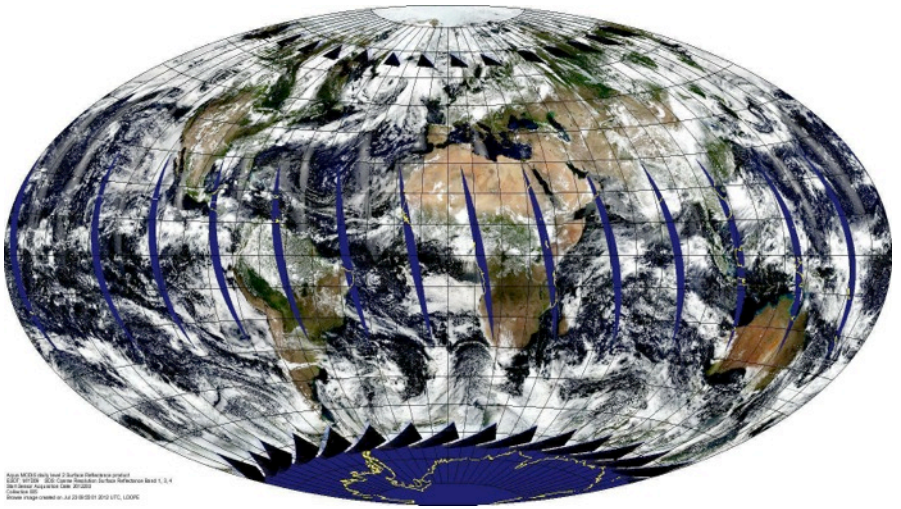
Calibration: On-board and continuously updated

Can observe: Clouds, Aerosols, Ocean Color, Temperature, Vegetation, Fires, etc.

Terra (10:30 Local Time, Descending)



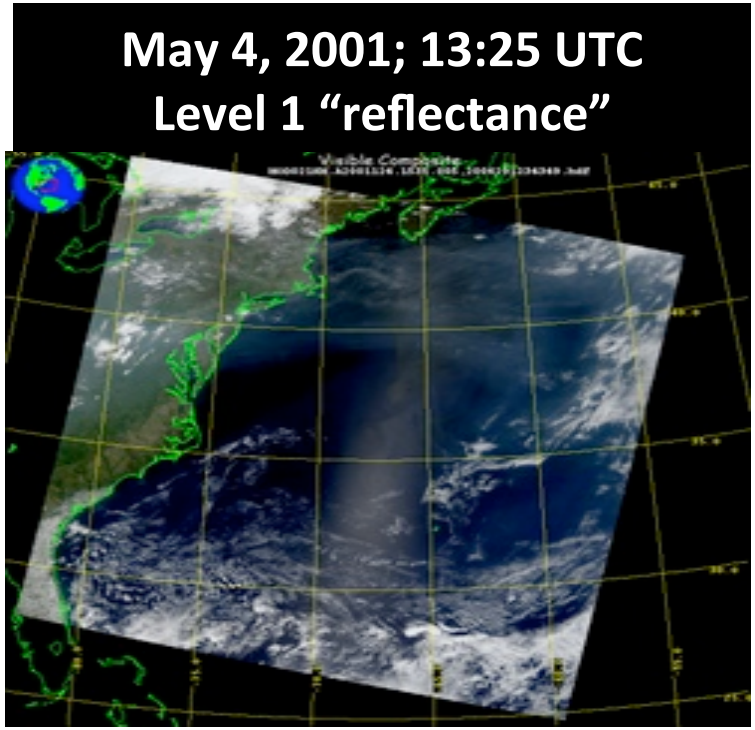
Aqua (13:30 Local Time, Ascending)



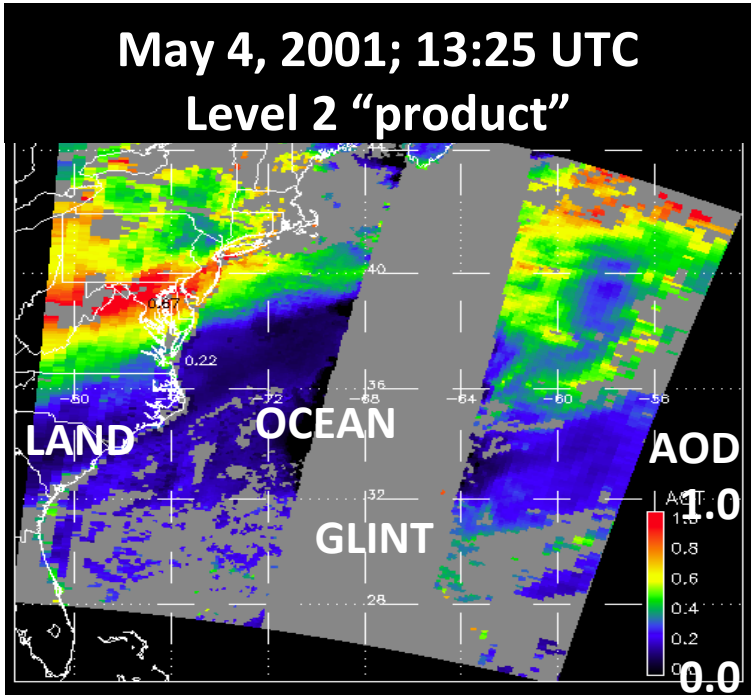
Twin MODIS instruments – Two views per day!

Aerosol retrieval from MODIS

What MODIS observes



Attributed to aerosol (AOD)

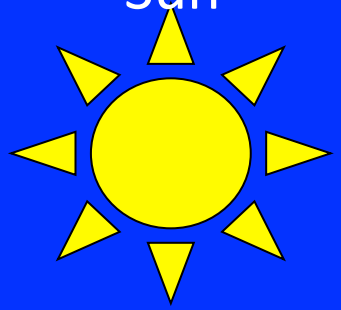


There are many different "algorithms" to retrieve aerosol from MODIS

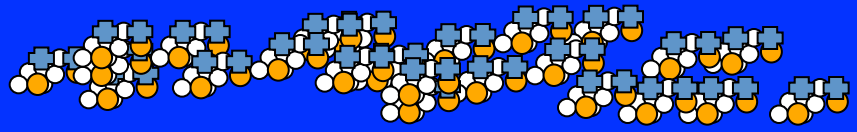
1. Dark Target ("DT" ocean and land; Levy, Mattoo, Munchak, Remer, Tanré, Kaufman)
2. Deep Blue ("DB" desert and beyond; Hsu, Bettenhousen, Sayer,..)
3. MAIAC (coupled with land surface everywhere; Lyapustin, Wang, Korkin,…)
4. Ocean color/atmospheric correction (McClain, Ahmad, …)
5. Etc (neural net, model assimilation, statistical, …)
6. Your own algorithm (many groups around the world)

Deconstruction of "Clear sky" Signal

Sun



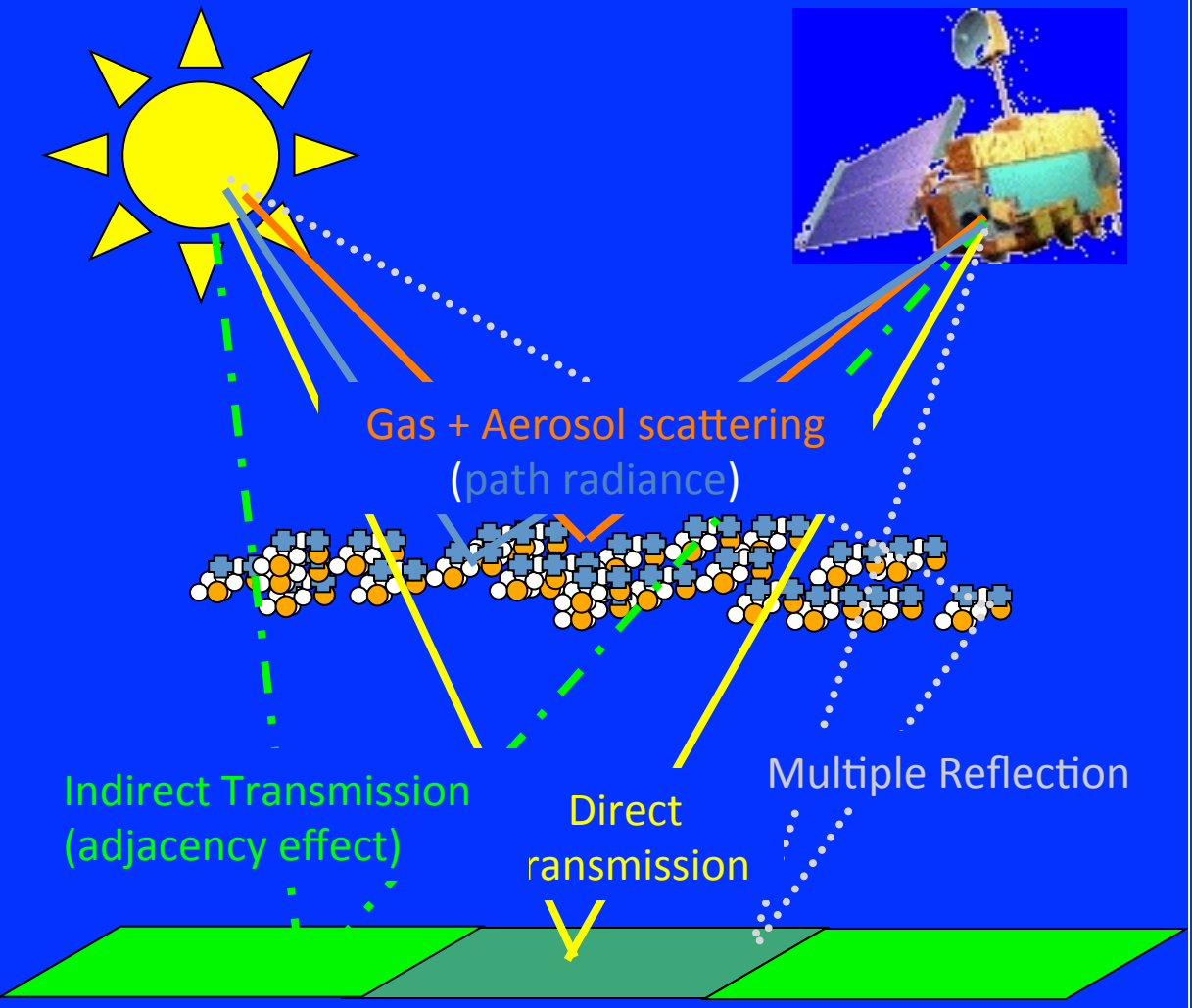
MODIS



Aerosol, Molecular, Gases

Dark Surface Target (Water or land)

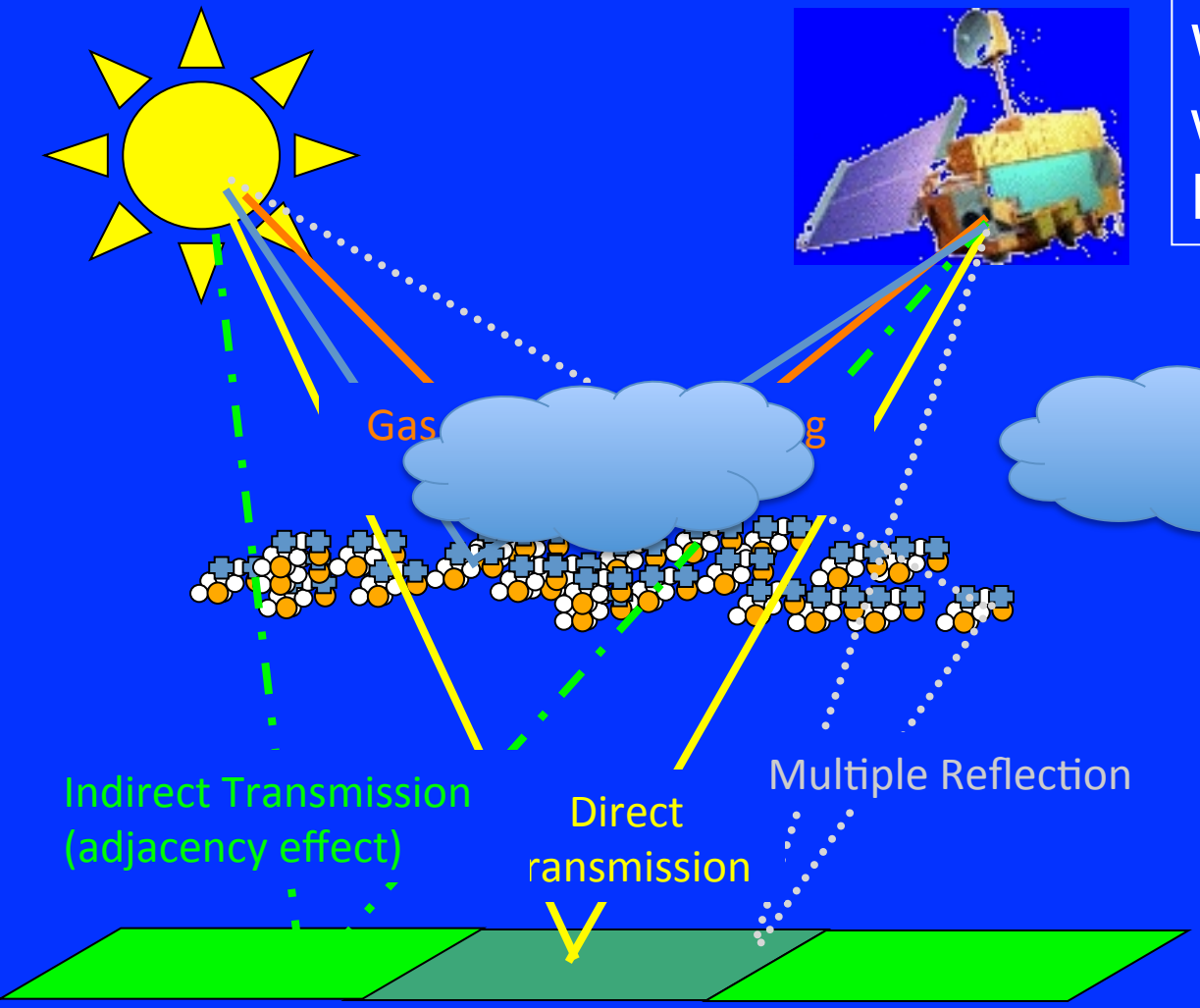
Complicated "Clear sky" TOA Signal



Contributions from:

- Gas absorption (O_3, CO_2, etc)
- H_2O absorption
- Rayleigh (molecular) scattering
- Aerosol scattering and absorption
- Surface reflection
- Atmosphere / Surface interaction
- Contamination from neighboring pixels (clouds, etc)
- ??

… And clouds (%@(*%@!)



We can not retrieve when cloudy.
Need a “cloud mask”

Construction of clear-sky TOA reflectance

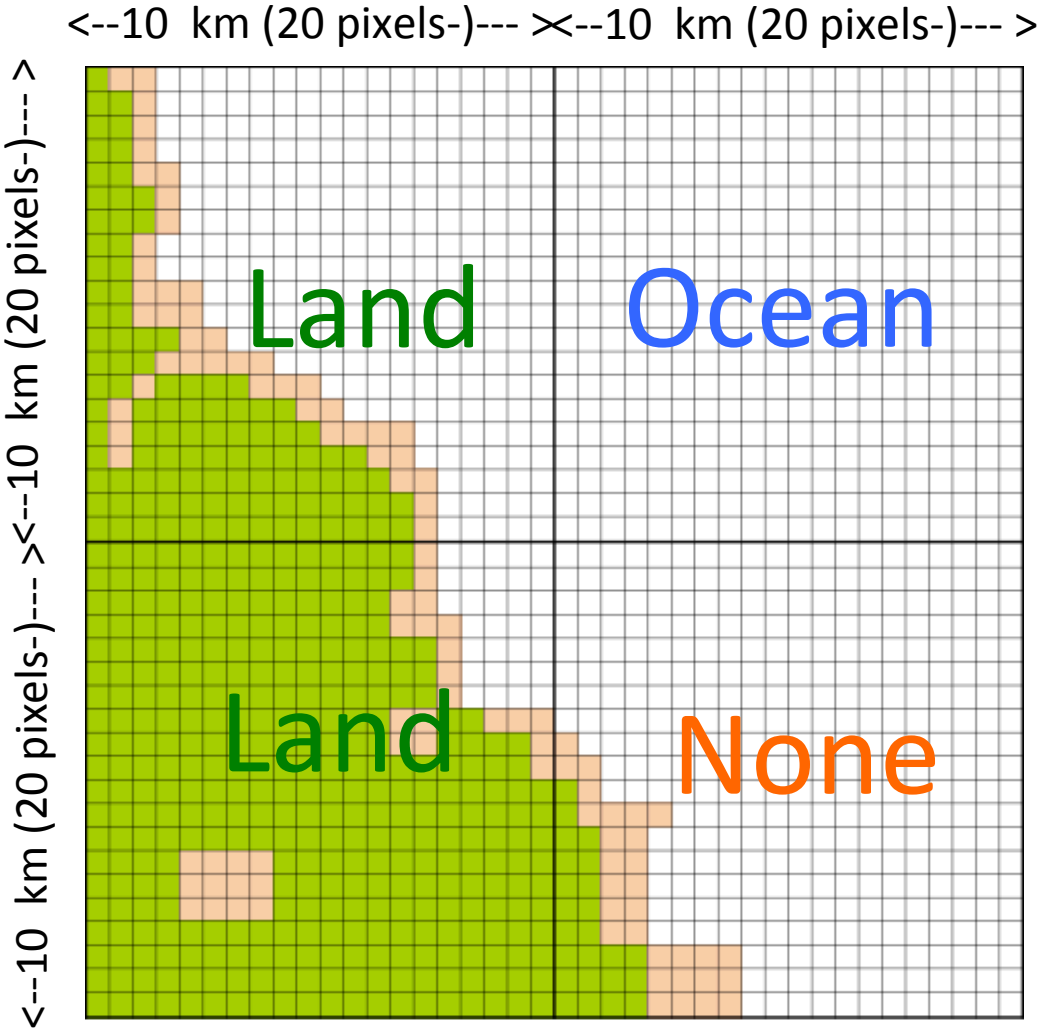
Total TOA reflectance

$$\rho_\lambda^*(\theta_0,\theta,\phi) = \rho_\lambda^a(\theta_0,\theta,\phi) + \frac{T_\lambda(\theta_0)T_\lambda(\theta)\rho_\lambda^s(\theta_0,\theta,\phi)}{1 - s_\lambda\rho_\lambda^s(\theta_0,\theta,\phi)} + \ldots$$

Path radiance
(what we want, sort of)

Surface reflectance contributions
(What we don't want)

Separate retrievals for ocean and land standard is 10 km products



Note that Deep Blue algorithm uses different bands that are 1 km, so 10 x 10 boxes for retrieval

We have removed clouds, found the best pixels, …..

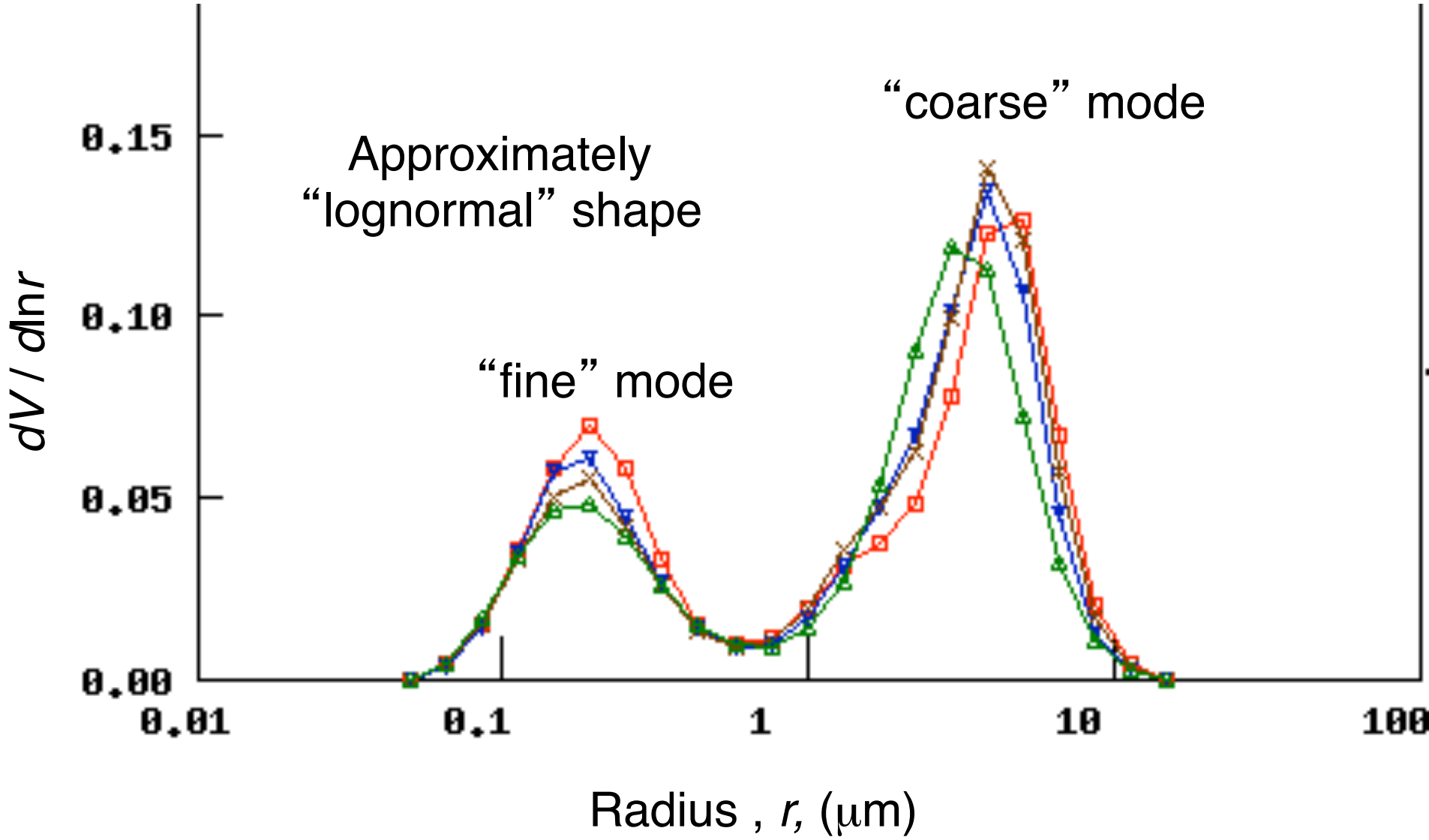
Retrieval Example (Ocean)

We need to make several assumptions to correctly Infer the aerosol characteristics from the remaining signal.

Assumptions include:

- Surface reflectance contribution as function of wind speed (whitecaps + glint + underwater radiance + …)
- Ambient aerosol is bi-modal (a superposition of “fine” and “coarse” aerosol)

Ambient Size Distribution



Physical properties of aerosol
Relationship to optical properties

If we assume:

- Size distribution: Superposition of lognormals, *i*,
  with radii $r_{v,i}$, standard deviation σ_i, and total volume $V_{0,I}$

- Spectral Complex Refractive index, $m_{\lambda,i}$
- Shape distribution: Spherical? Spheroids?

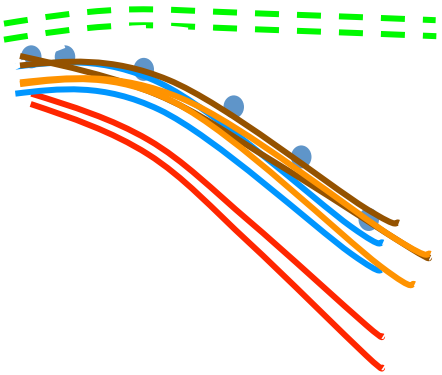
Then, we can compute spectral scattering / absorption (extinction) properties (e.g. Mie or T-matrix theory)

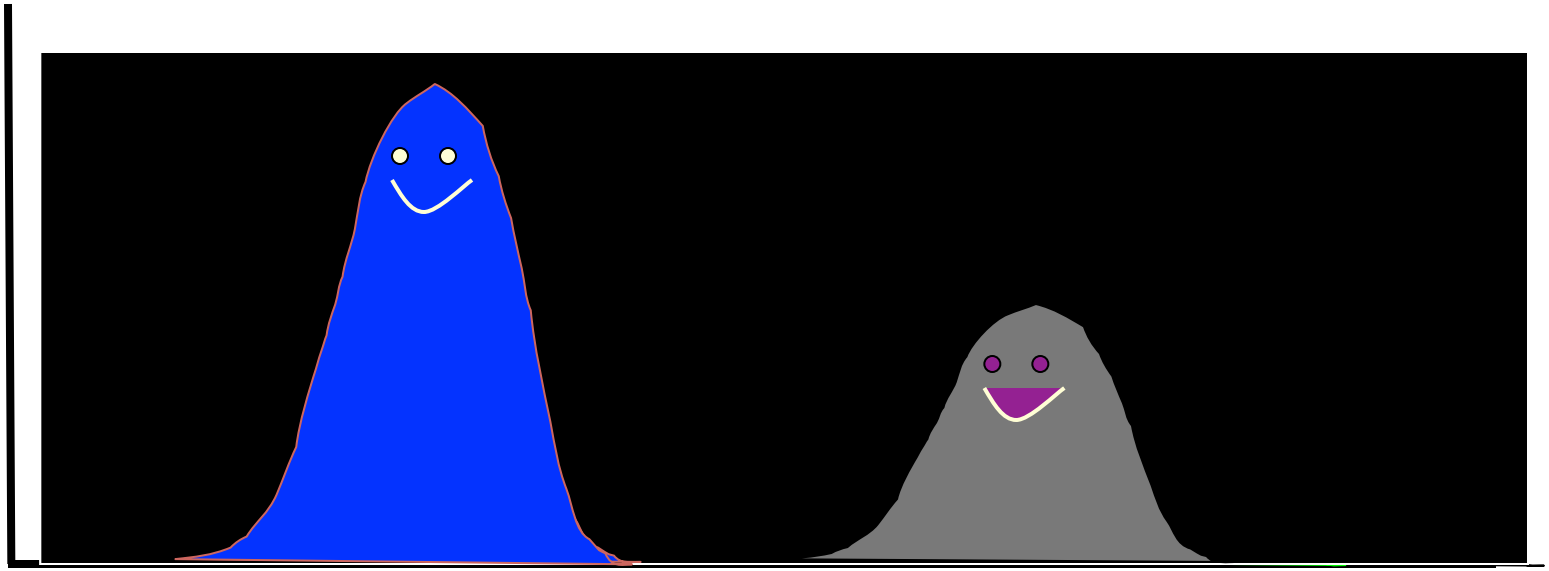
And then we can use Radiative transfer to simulate TOA reflectance
These are called "lookup tables" (LUTs)

$$\rho_\lambda^*(\theta_0,\theta,\phi) = \rho_\lambda^a(\theta_0,\theta,\phi) + \frac{T_\lambda(\theta_0)T_\lambda(\theta)\rho_\lambda^s(\theta_0,\theta,\phi)}{1 - s_\lambda\rho_\lambda^s(\theta_0,\theta,\phi)} + \ldots$$

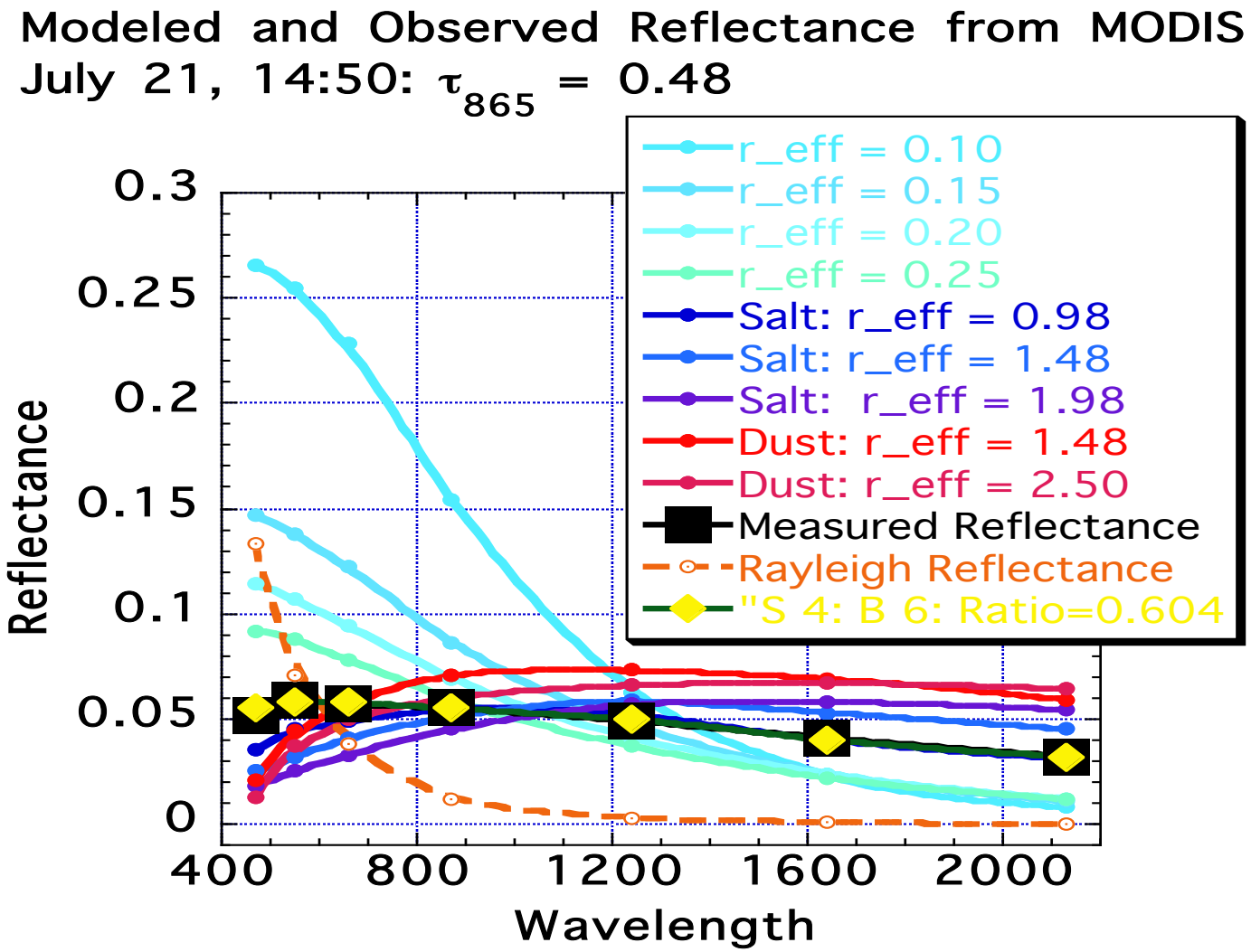
MODIS aerosol retrieval over ocean

Find one coarse mode and
one fine mode
that combine to match the
observed spectral reflectances





MODIS Ocean Aerosol Retrieval



Remote Sensing of Spectral Aerosol Properties: A Classroom Experience
(Levy and Pinker, BAMS, 2007)

Over land, must make extra assumptions

- Dark targets: Surface reflectance contribution is related spectrally

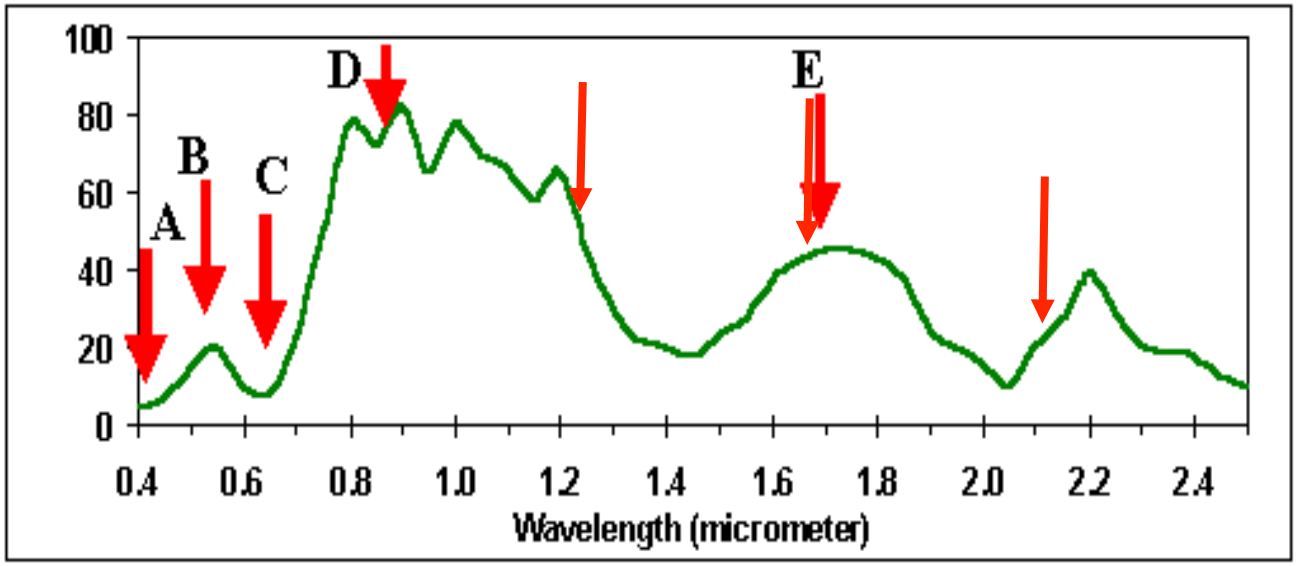
Vegetation reflectance:

$\rho^s_{0.66} \approx 0.55\rho^s_{2.1}$

$\rho^s_{0.47} \approx 0.50\rho^s_{0.66}$

Depends on

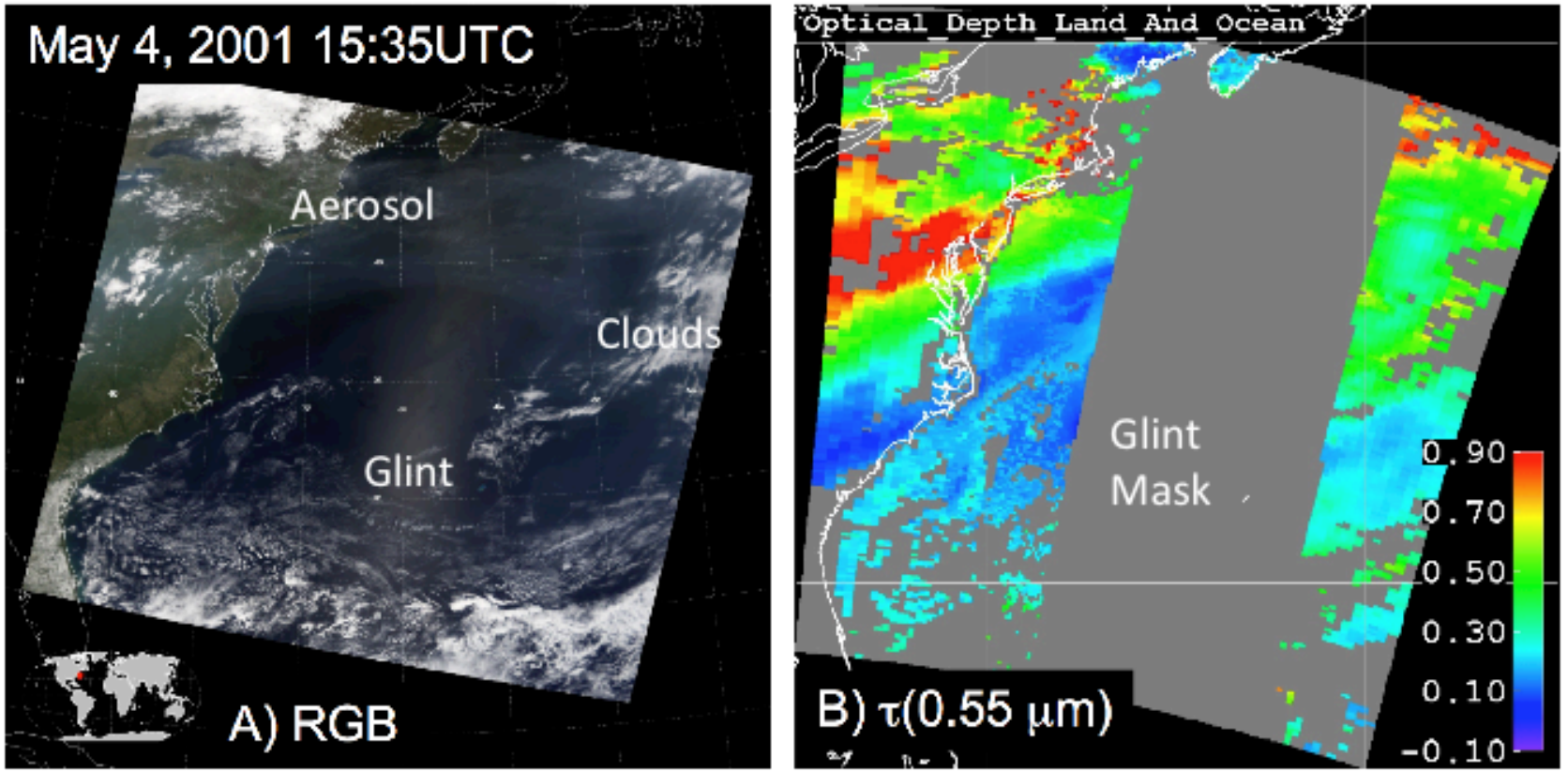
$\rho_{0.86}, \rho_{1.2}, \rho_{2.1}$ and Θ



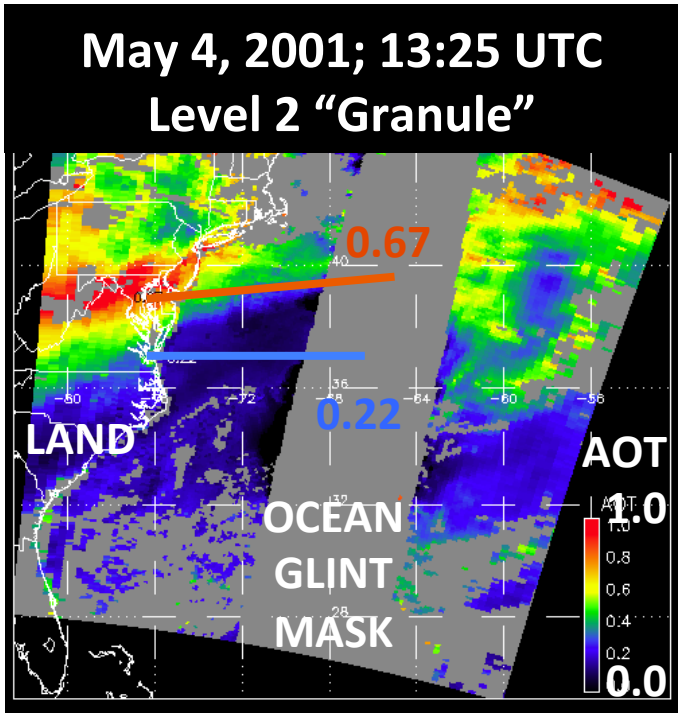
- Ambient aerosol is multi-modal (a superposition of “fine” and “coarse” aerosol models, each are bi-modal).

- Aerosol type is related to when in the year, and where in the world. We have to assume aerosol type

aerosol retrieval combined land/ocean (dark target)

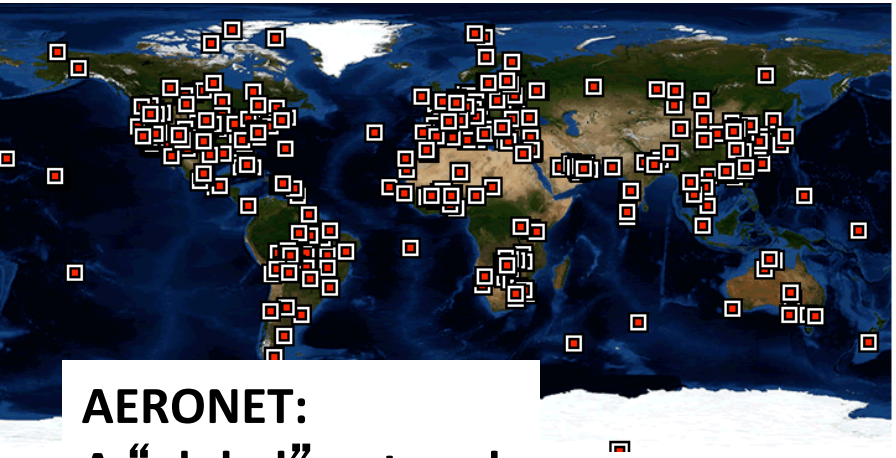


Validation: quantifying the expected error

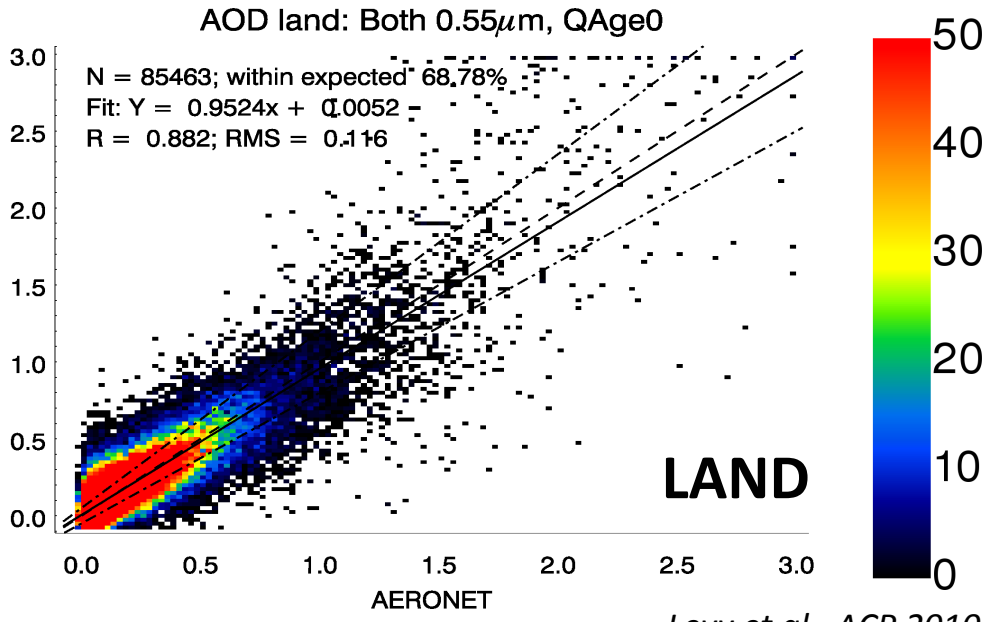


Compare both land and ocean products to sunphotometer, separately

- Validation: 66% are within "Expected Error" (EE) defined as
  - Land: $\pm(0.15\tau + 0.05)$
  - Ocean: $\pm(0.05\tau + 0.04)$



AERONET:
A "global" network

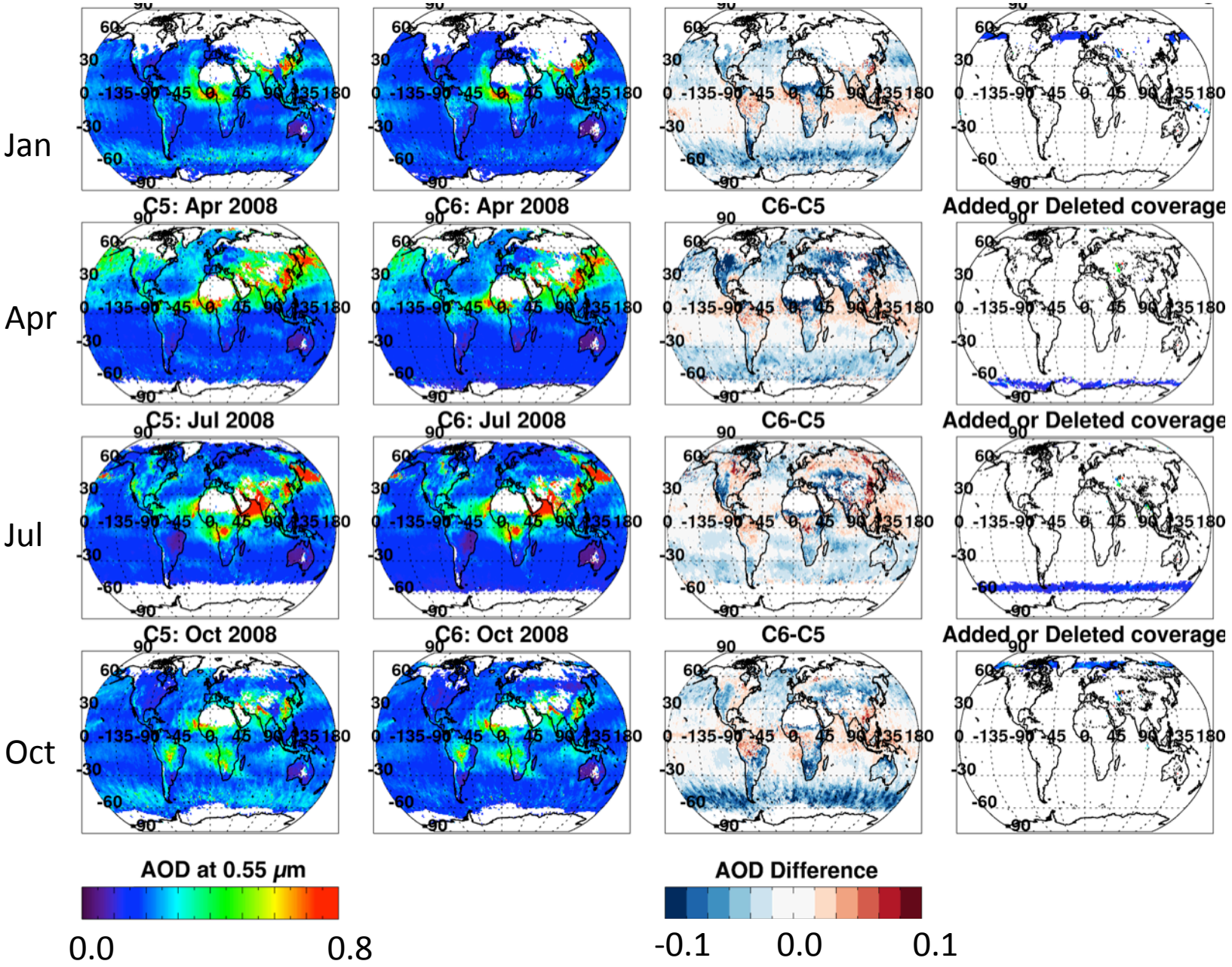


Levy et al., ACP 2010

MODIS Collection 6 updates (Dark target)

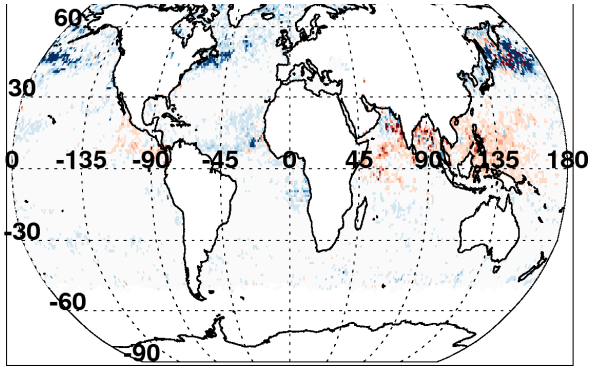
- Specifically, the 10 km standard product (MxD04_L2)
- There is a new higher resolution product (3km: MxD04_3K), which is interesting for air quality applications, but that is for another day!
- There is also a new Deep Blue/ Dark-target "merge" product, and Deep Blue is improved greatly everywhere, but that is also for another day.

Overall changes (C6 vs C5): Aqua, 2008

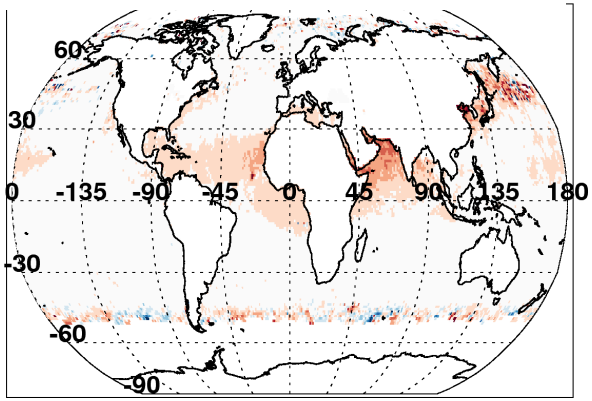


C6-C5 ocean: Due to many incremental changes (Aqua, July 2008)

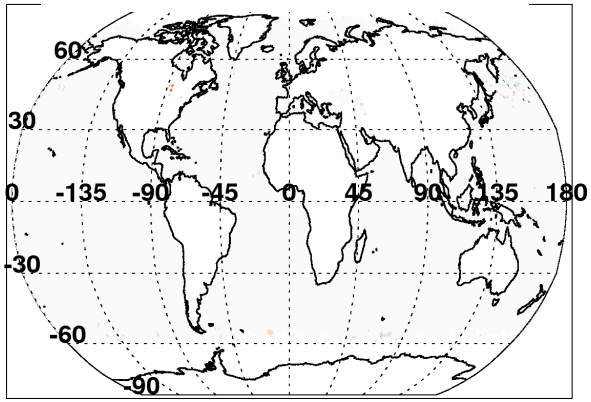
New reflectance, geo-location inputs, Wisconsin cloud mask



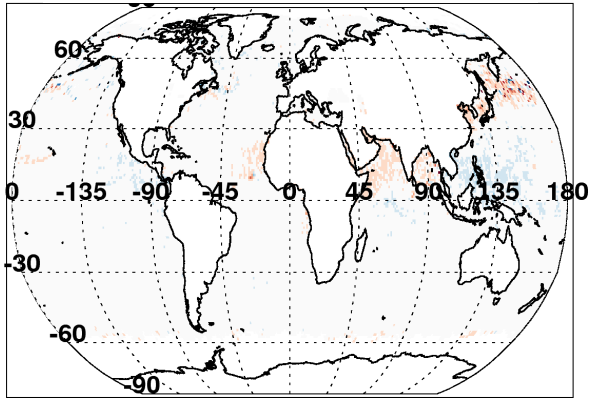
Updated radiative transfer



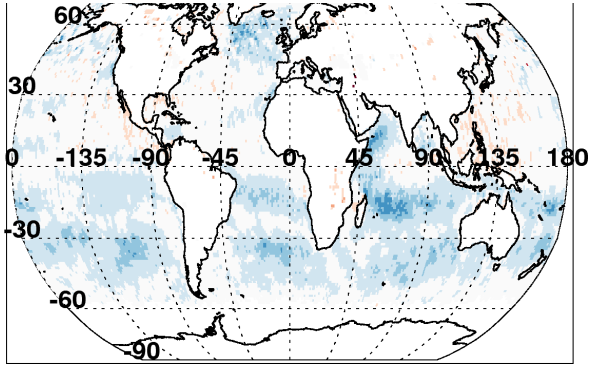
Re-define land and sea



Improved cloud mask



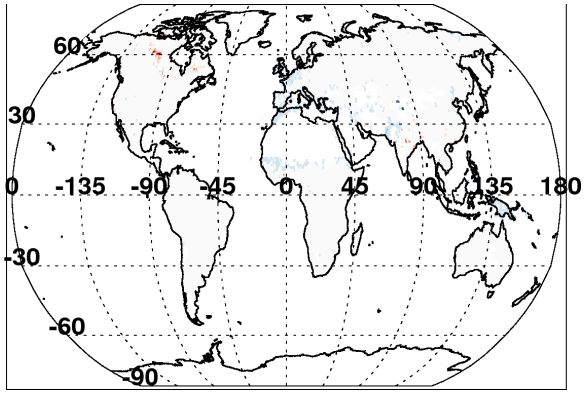
Account for wind speed impact on surface



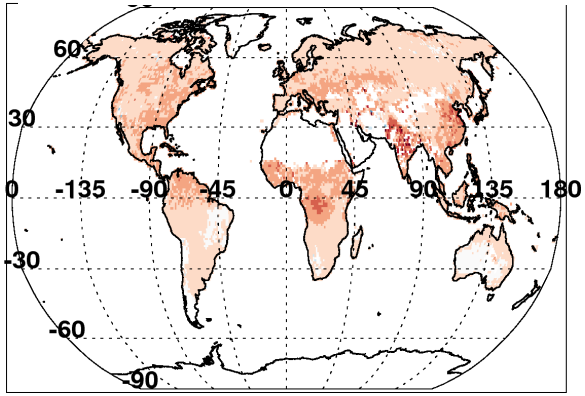
- Also changed "Quality Assurance" Filtering
- Changed aerosol definitions of land and sea
- Etc

C6-C5 land: Due to many incremental changes (Aqua, July 2008)

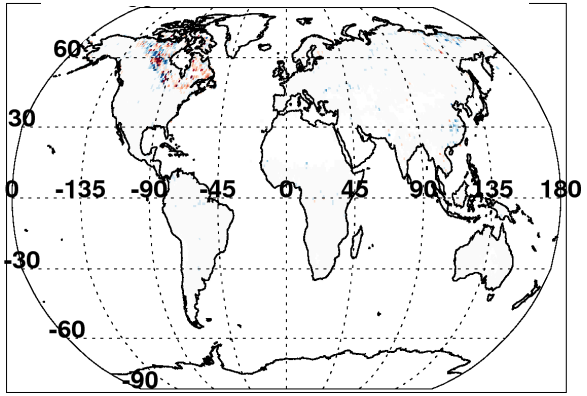
New reflectance and geo-location inputs



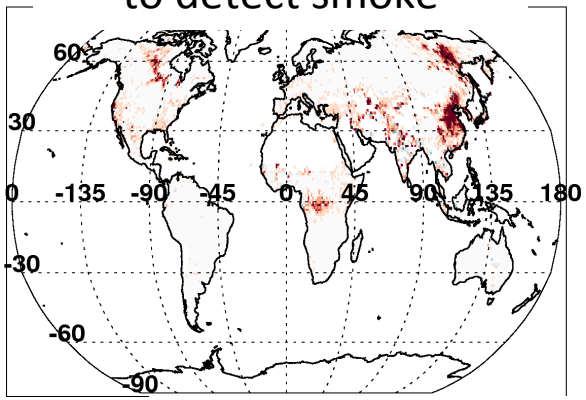
Updated radiative transfer



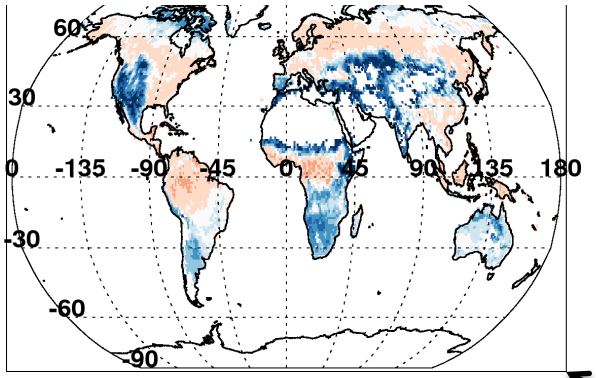
Re-define land and sea

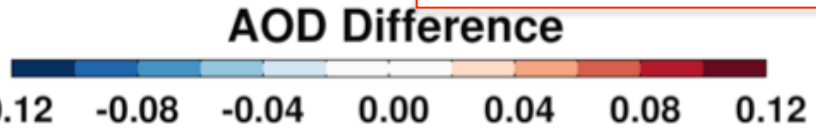


Improved cloud mask to detect smoke



Fixed surface reflectance assumptions

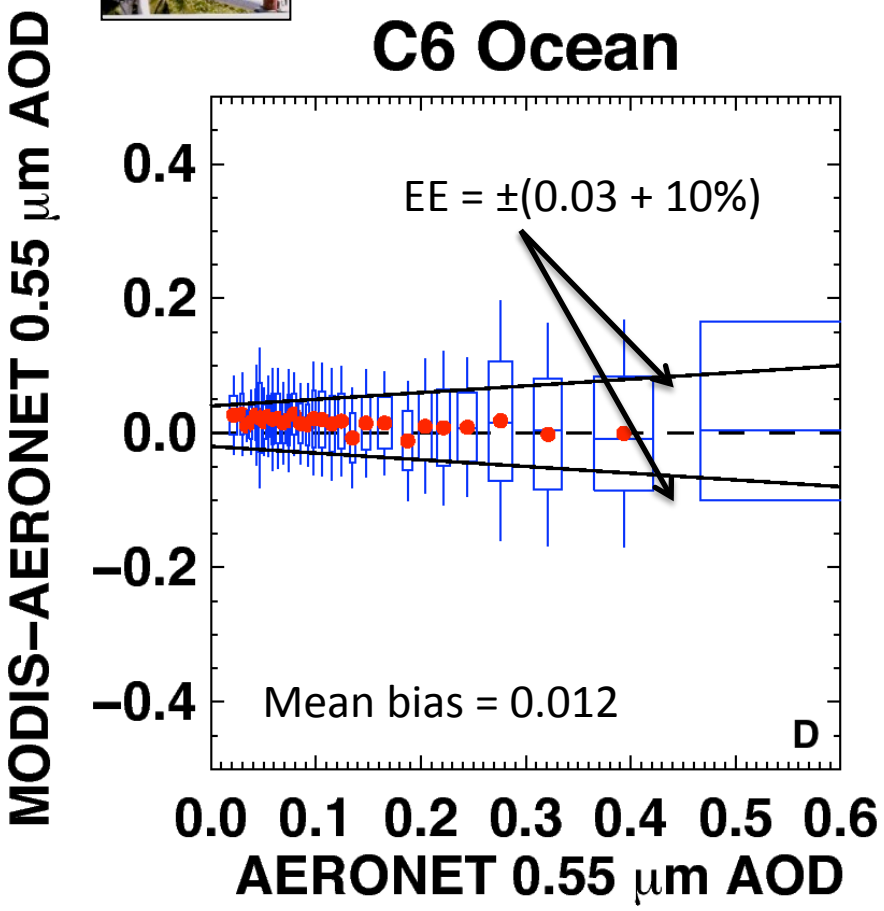


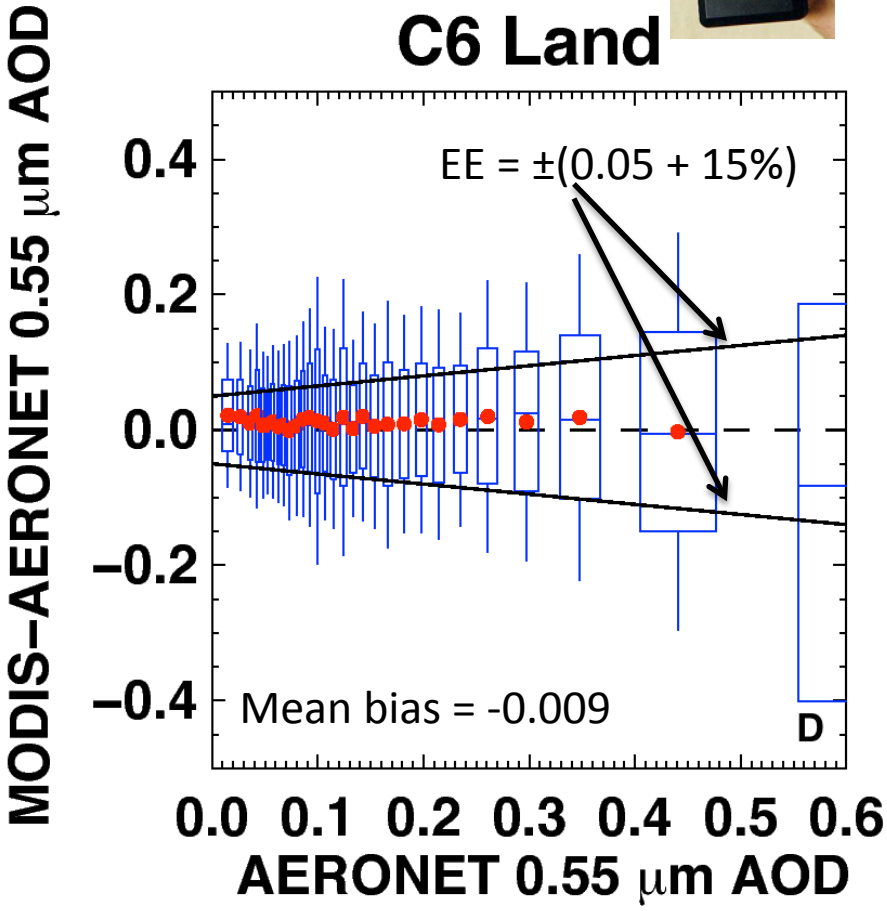


- Also changed "Quality Assurance" Filtering
- Changed aerosol definitions of land and sea
- Etc

This was a major bug!

C6: Aqua MODIS compared to AERONET (based on 8 months of test data)





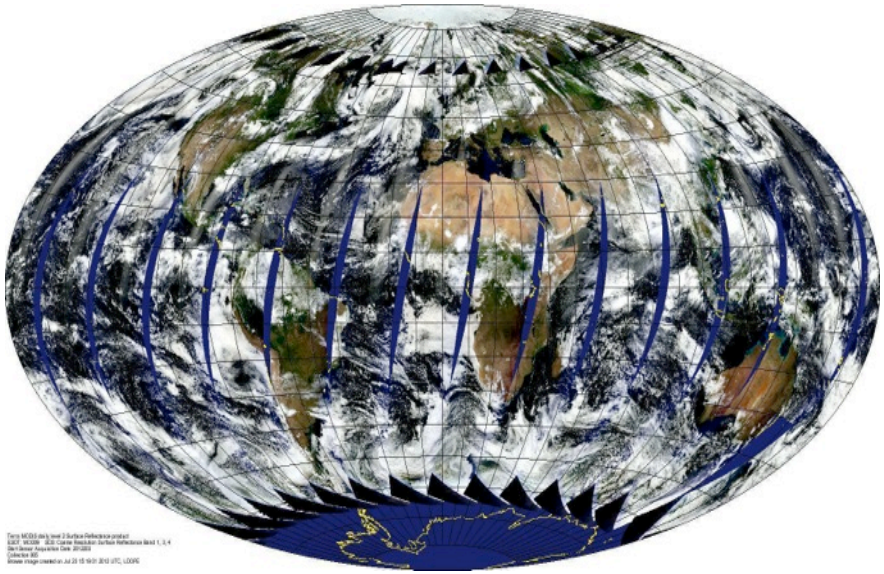
- Larger uncertainty for individual Aqua-MODIS retrievals
- Where collocated, global MODIS mean agrees to AERONET within ±0.015 over both land and ocean

Figs from Levy et al., AMT 2013

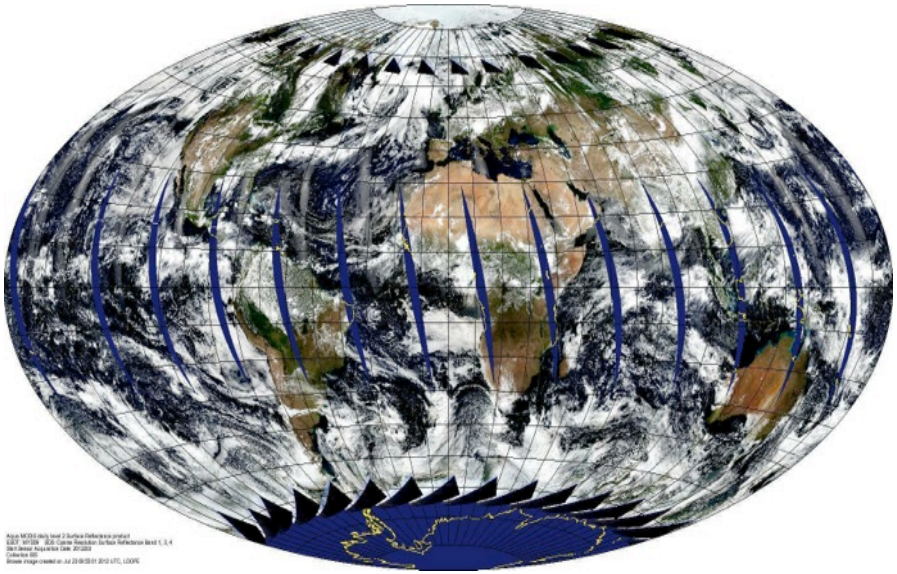
Focus on Calibration issues

Two MODIS instruments = “identical twins”

Terra (since spring 2000)

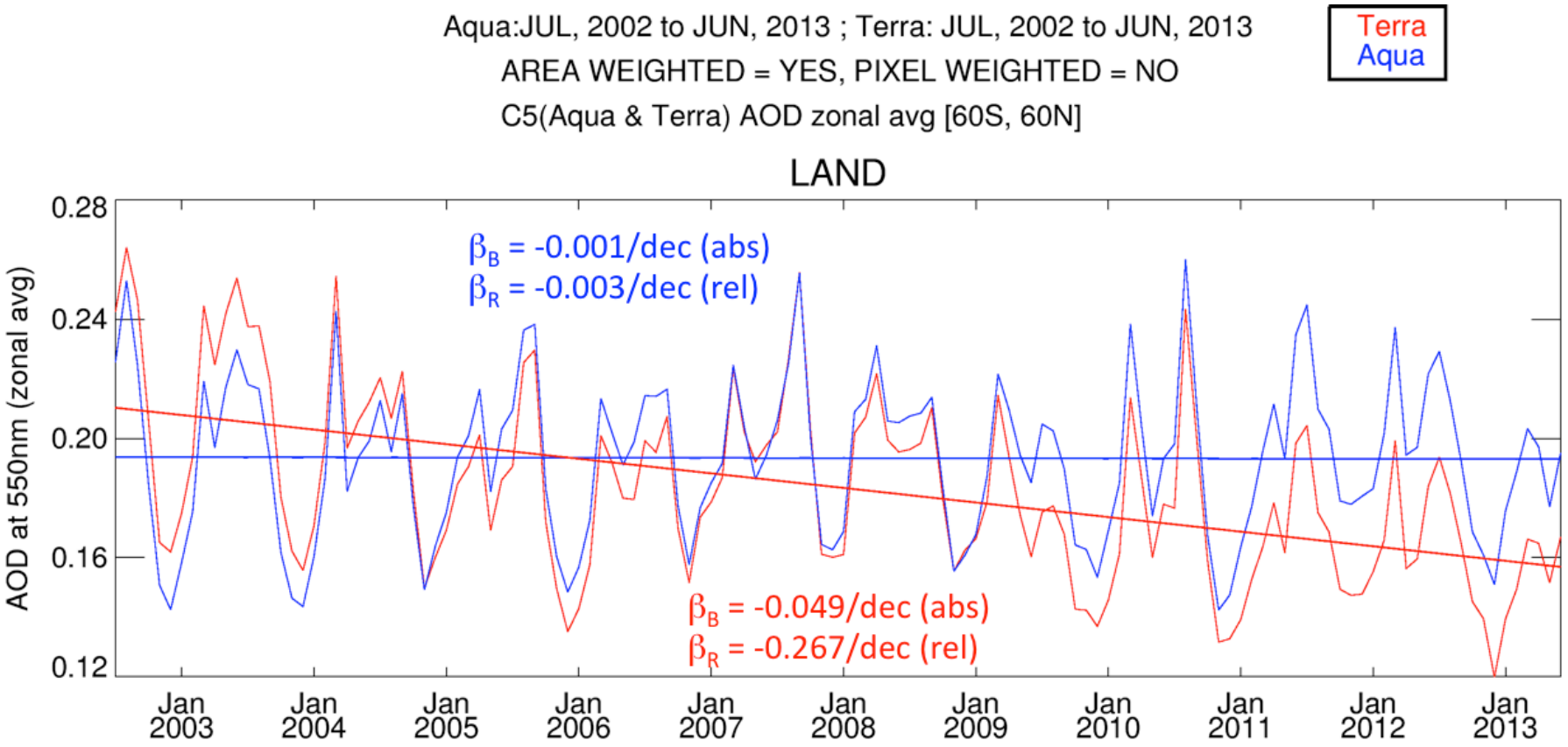


Aqua (since summer 2002)



- Same instrument hardware (optical design)
- Same spatial and temporal sampling resolution
- Same calibration/processing teams
- Same aerosol retrieval algorithms

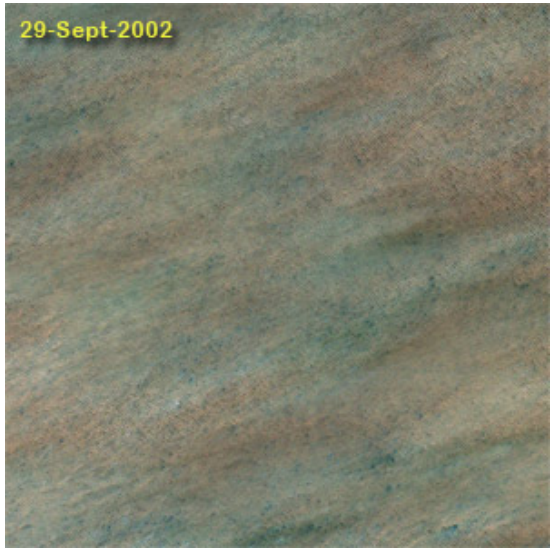
Aerosol Trends: If based on Collection 5



- Over land, Terra *decreased* (-0.05/decade), Aqua *constant*
- Terra / Aqua divergence was similar everywhere on the globe!

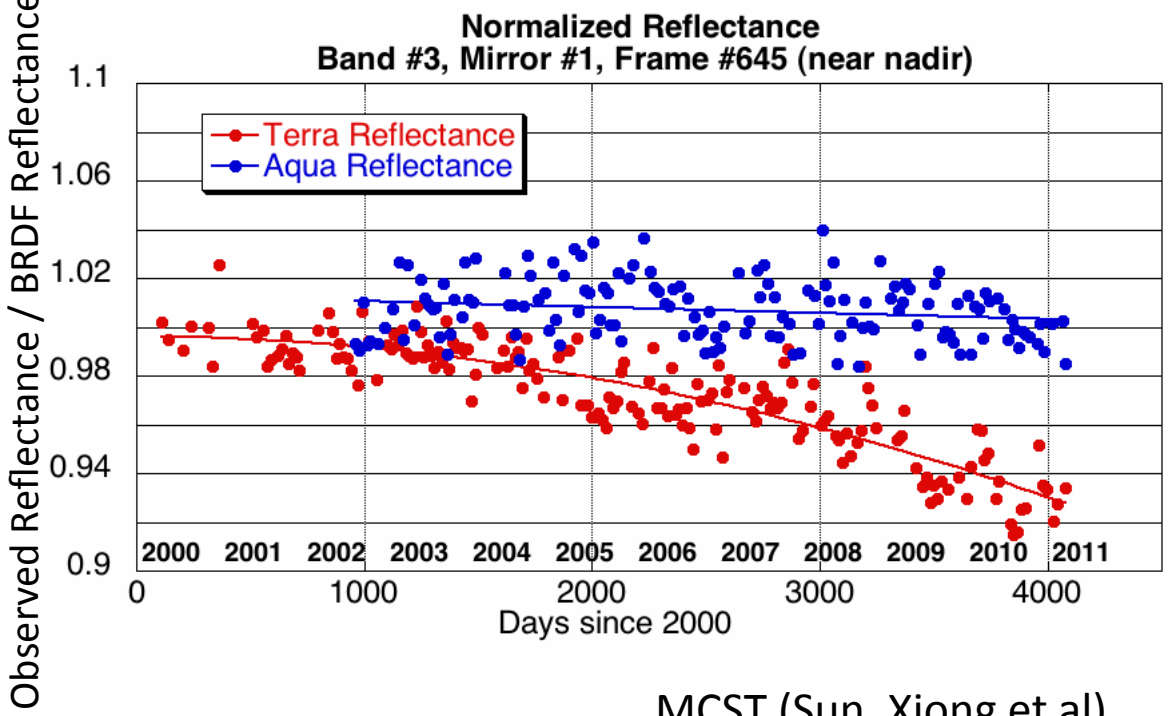
- Like identical human twins, the twin MODIS sensors aged differently.

Tracking MODIS RSB radiometric stability from reflectance trends over CEOS desert sites



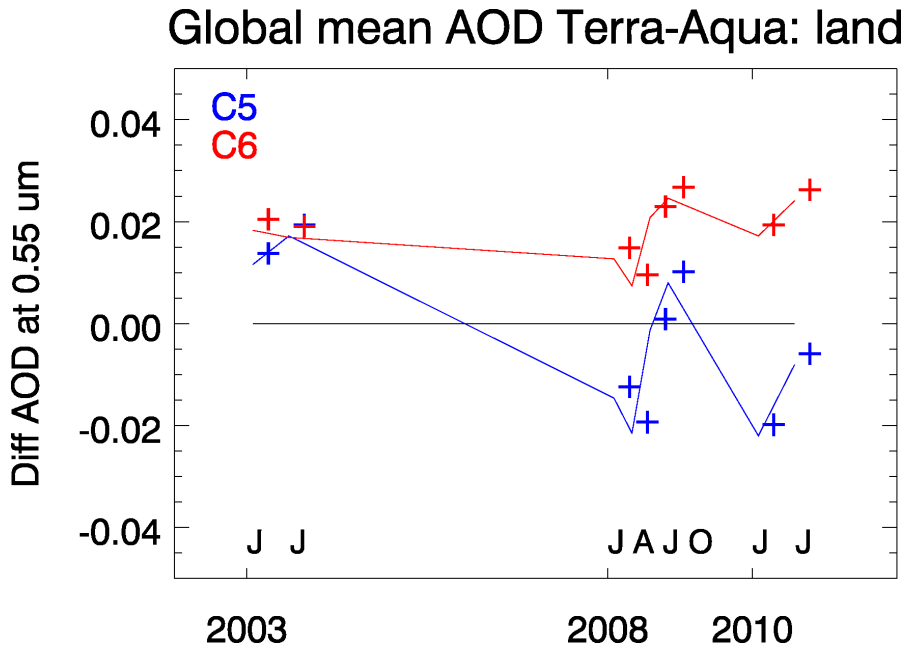
CEOS desert test sites

(1) Collect clear-sky MODIS data over desert sites
(2) Develop site-specific BRDF from first 3 years of mission
(3) Over time, compare "observed" reflectance with BRDF modeled reflectance, for different view angles
(4) Trends in Band #3 (0.47 μm) are consistent with Terra's AOD trends over LAND!
(5) → NEW CALIBRATION METHOD applied to Terra!



MCST (Sun, Xiong et al)

Impact of new calibration on trend of Terra-Aqua AOD



- 8 months processed with same dark-target aerosol algorithms and new calibration
- Terra now more "in sync" with Aqua time series
- **New calibration → Terra/Aqua divergence removed for C6!**
- (Terra-Aqua) offset remains 0.02 (land) and 0.015 (ocean)

Calibration issues

- While C005 was "validated"…
  - The C005 data record did not agree for Terra and Aqua trends
  - Divergence was traced to calibration, which is mostly fixed.
  - We made many improvements to algorithm as well
- C006 has remaining Terra/Aqua differences (0.015 offsets = 10%) that we are trying to understand.
  - Are these real AOD differences?
  - Are these due to calibration offsets?
  - Are these due to cloud differences (and aerosol sampling) between morning and afternoon?
- Calibration still may be improved

Lyapustin, A., Wang, Y., Xiong, X., Meister, G., Platnick, S., Levy, R., Franz, B., Korkin, S., Hilker, T., Tucker, J., Hall, F., Sellers, P., Wu, A. and Angal, A.: Scientific impact of MODIS C5 calibration degradation and C6+ improvements, Atmos Meas Tech, 7(12), 4353–4365, doi:10.5194/amt-7-4353-2014, 2014.

Summary (MODIS C6)

- MODIS aerosol retrieval ("MxD04_L2") has many upgrades for Collection 6.
- Aqua/Terra level 2 and 3 are available now
- Dark target (DT) updates
- Trending issues reduced with new calibration efforts
- Read papers and documents if you want more information (next page).

MODIS (MxD04) Collection 6!

- Levy, R. C., Mattoo, S., Munchak, L. A., Remer, L. A., Sayer, A. M., Patadia, F. and Hsu, N. C.: The Collection 6 MODIS aerosol products over land and ocean, Atmos Meas Tech, 6(1), 2989–3034, doi:10.5194/amt-6-2989-2013, 2013.
- Sayer, A. M., Munchak, L. A., Hsu, N. C., Levy, R. C., Bettenhausen, C. and Jeong, M. J.: MODIS Collection 6 aerosol products: Comparison between Aqua's e-Deep Blue, Dark Target, and 'merged' data sets, and usage recommendations, J Geophys Res-Atmos, n/a–n/a, doi: 10.1002/2014JD022453, 2014.
- Munchak, L. A., Levy, R. C., Mattoo, S., Remer, L. A., Holben, B. N., Schafer, J. S., Hostetler, C. A. and Ferrare, R. A.: MODIS 3 km aerosol product: applications over land in an urban/suburban region, Atmospheric Measurement Techniques Discussions, 6(1), 1683–1716, doi:10.5194/amtd-6-1683-2013, 2013.
- Remer, L. A., Mattoo, S., Levy, R. C. and Munchak, L. A.: MODIS 3 km aerosol product: algorithm and global perspective, Atmos Meas Tech, 6(7), 1829–1844, doi:10.5194/amt-6-1829-2013, 2013.

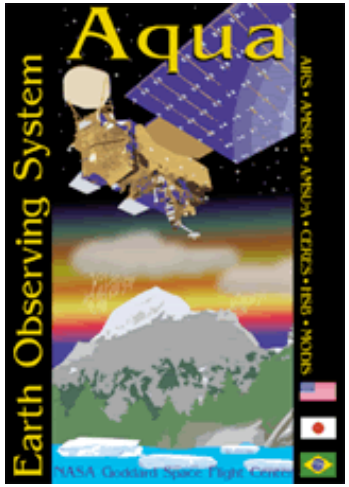
Collection 6 "Webinars": http://aerocenter.gsfc.nasa.gov/ext/registration/

New "dark-target" website: http://darktarget.gsfc.nasa.gov

MODIS product website: http://modis-atmos.gsfc.nasa.gov

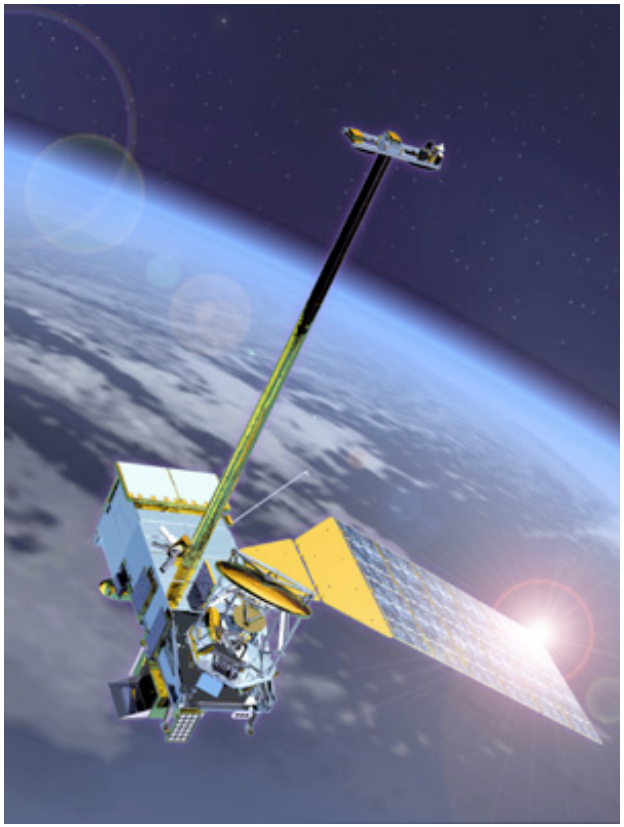
Terra just celebrated its 15th birthday!

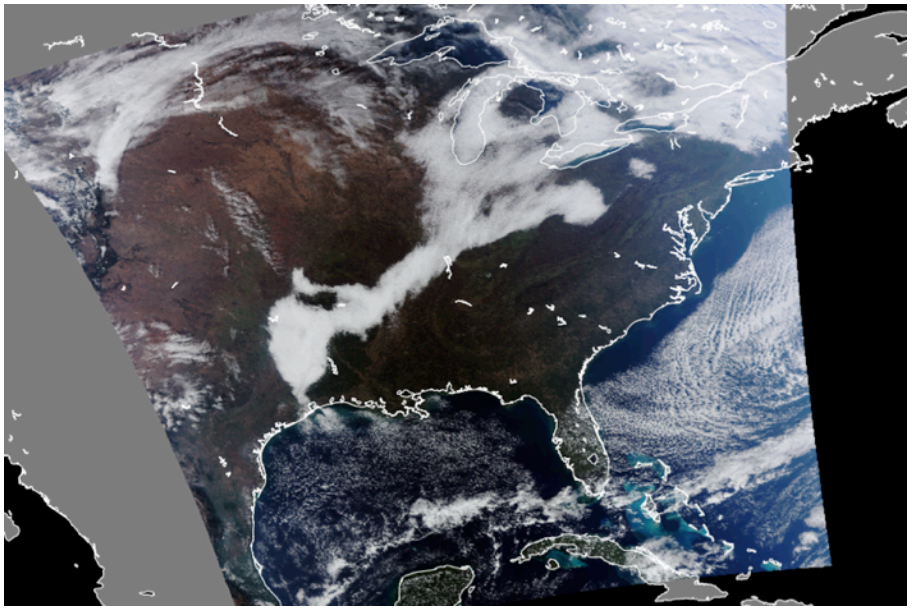
- At twelve - Aqua ain't no spring chicken!
- Terra and Aqua MODIS instruments are both 3x original mission lifetimes
- MODIS won't be here forever
- How do we get to 20+ year aerosol data records?



Beyond MODIS

Suomi-NPP (and future JPSS) VIIRS
Visible Infrared Imager Radiometer Suite





Can VIIRS “continue” the MODIS aerosol data record?

VIIRS versus MODIS

Orbit: 825 km (vs 705 km), sun-synchronous, over same point every 16 days
Equator crossing: 13:30 on Suomi-NPP, since 2012 (vs on Aqua since 2002)

Swath: 3050 km (vs 2030 km); Granule size: 86 sec (vs 5 min)

Spectral Range: 0.412-12.2μm (22 bands versus 36 bands)

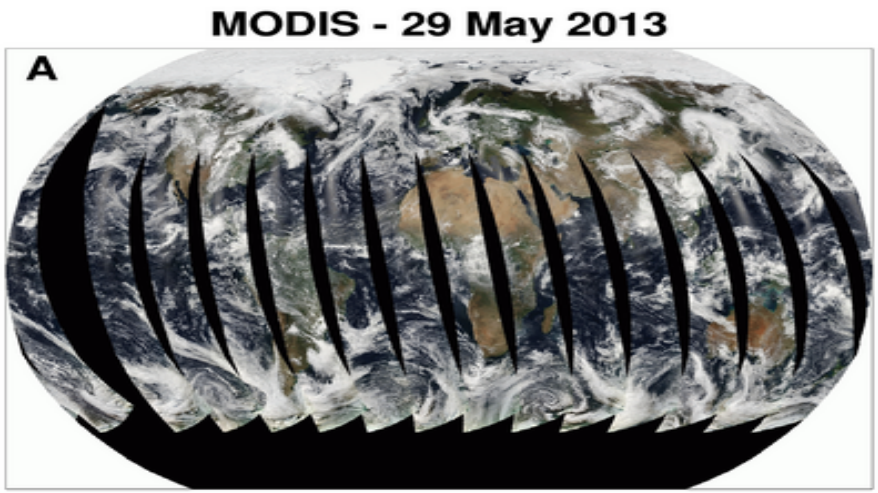
Spatial Resolution: 375m (5 bands) 750m (17 bands): versus 250m/500m/1km

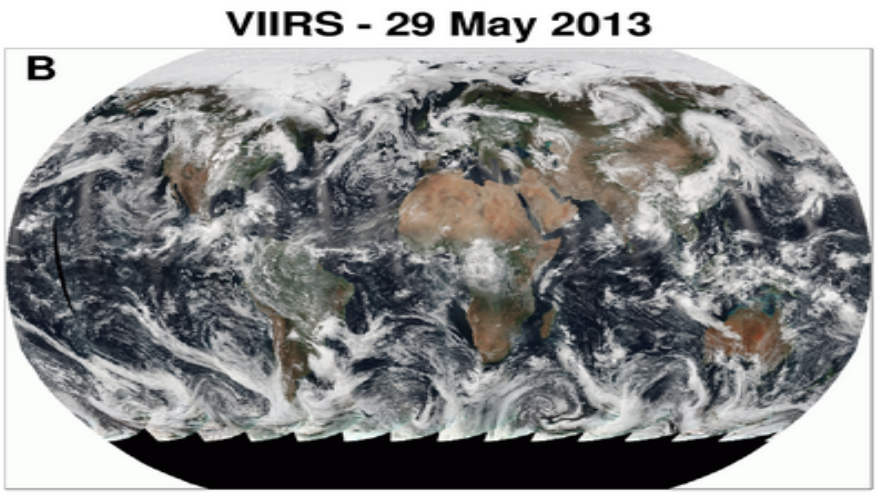
Aerosol retrieval algorithms: "Physics" similar, but different strategies

Wavelength bands (nm) that could be used for DT aerosol retrieval: 482 (466), 551 (553) 671 (645), 861 (855), 2257 (2113) → differences in Rayleigh optical depth, surface optics, gas absorption.

Aqua (13:30 Local Time, 14.6 revs/day)

Suomi-NPP (13:30 Local Time 14.1 revs/day);



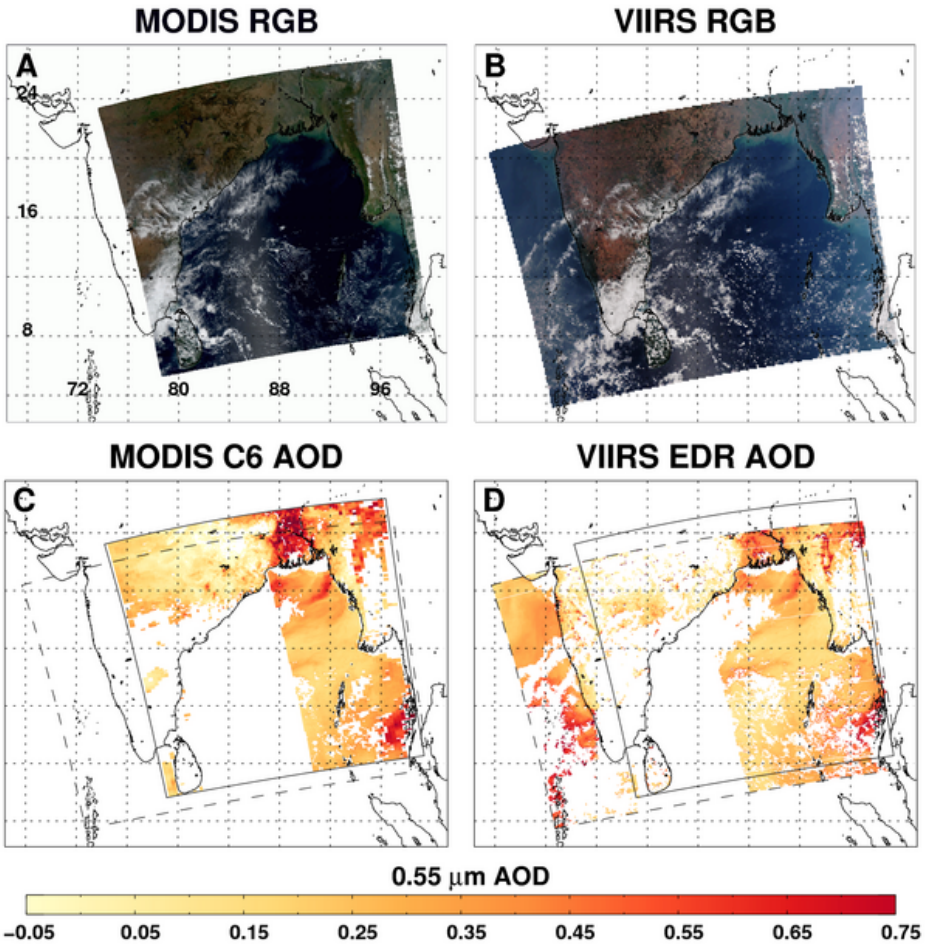


VIIRS Aerosol Algorithm (NOAA-IDPS)

- Multi-spectral over dark surface
- Separate algorithms used over land and ocean
- Algorithm heritages
  - over land: MODIS atmospheric correction (e.g. the MOD09 product)
  - over ocean: MODIS aerosol retrieval (MOD04 product)
- Many years of development work:
- Retrieves: AOD (at 0.55 μm and spectral), Ångström Exponent (AE), Suspended Matter (aerosol classification), etc
- NOAA CLASS: The Primary Gateway for the VIIRS Data Distribution
- "Validated Stage 2" (published) since 23 Jan 2013.
- Provides data in HDF5 format (compared to HDF4-ish for MODIS)

Aerosol retrieval: Different algorithms

Granules over India (Mar 5, 2013, 0735/0740 UTC)



Ocean retrieval algorithm

- "heritage" circa 1997 (Tanré, Kaufman, Remer,…)

- MODIS: C6 assumptions (Levy et al., 2013)
- VIIRS: C5-like assumptions (Remer et al., 2005)

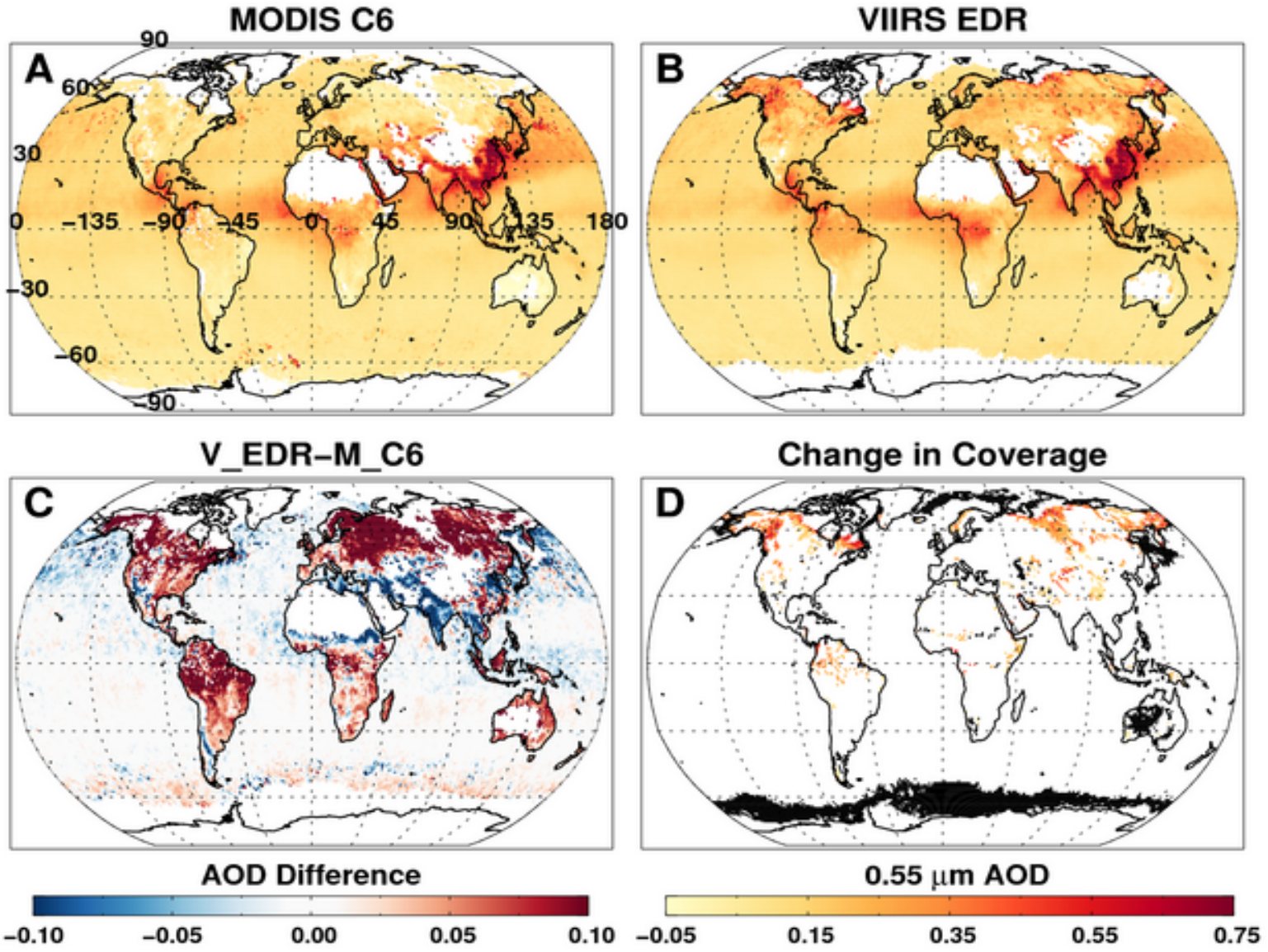
Land retrieval algorithm

- "heritage" circa 1997 (Kaufman, Tanré, Vermote,…)

- MODIS: C6 "dark-target" (Levy et al., 2007, 2013)
- VIIRS: C5 "atmos. correction" (Vermote et al., 2008).

- Differences in wavelengths, cloud masks, pixel selection technique, quality assurance etc:
- Also, not exactly overlapping orbits (note 5 min difference).
- Note, 86 second VIIRS granules aggregated to 5 minutes.

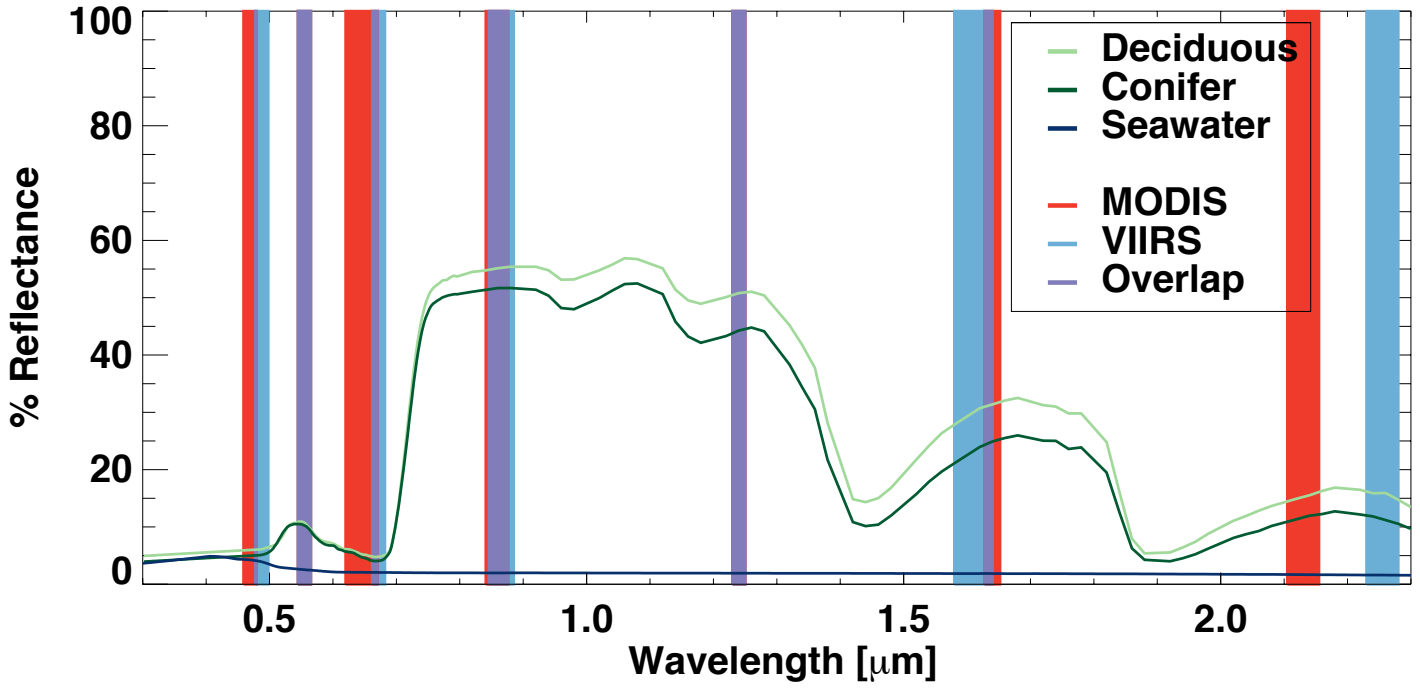
Monthly mean AOD for Spring 2013 (Mar-May)



MODIS C6 and VIIRS-EDR are similar, yet different

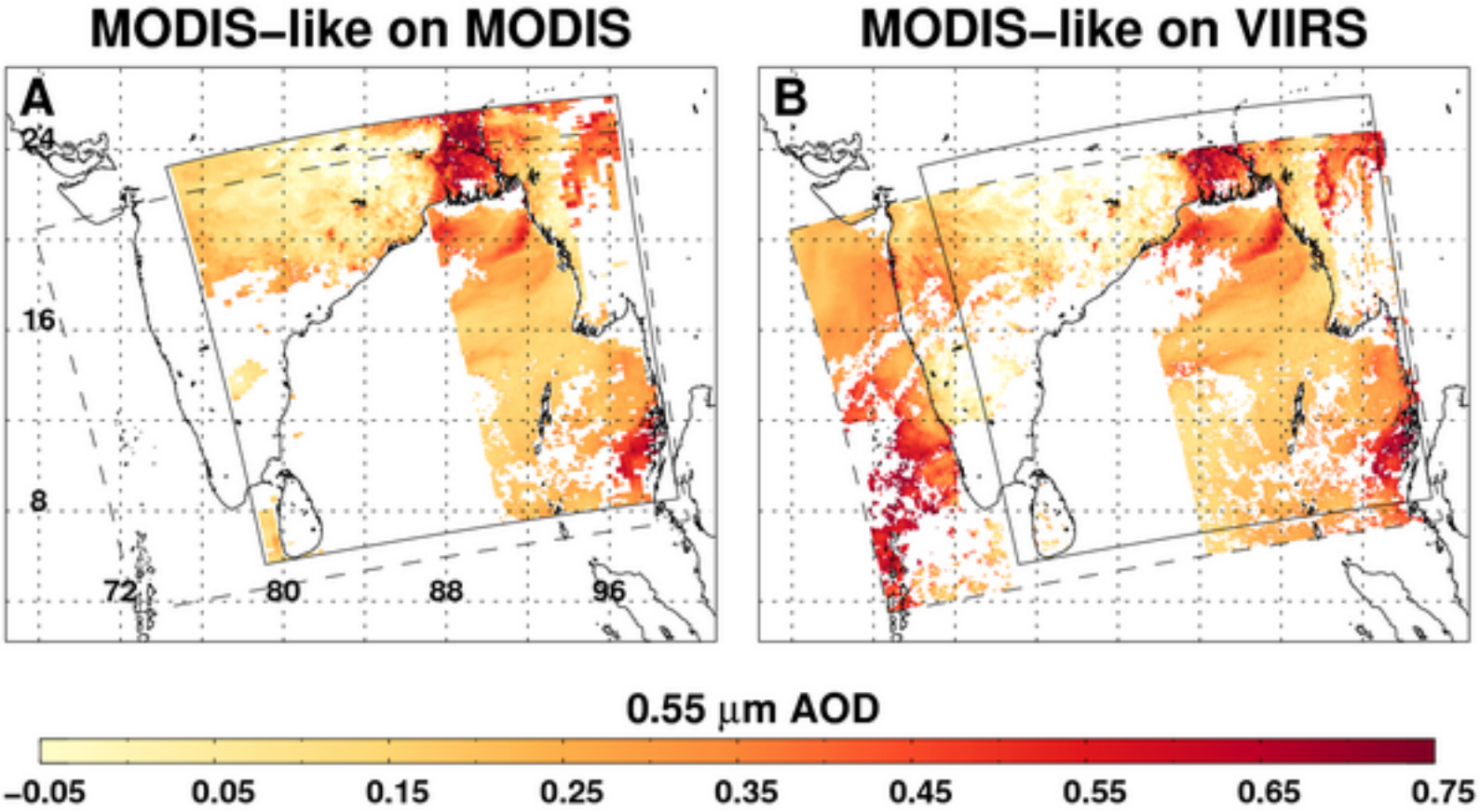
Create a MODIS like algorithm for VIIRS?

- The Intermediate file format (IFF) puts MODIS and VIIRS in “same common denominator” (University of Wisconsin)
- MODIS-IFF is 1 km resolution for all bands, VIIRS-IFF is 750 m (no high-resolution bands for either MODIS or VIIRS)
- Use 10 x 10 pixel retrieval boxes (so 10 km for MODIS; 7.5 km for VIIRS).
- Run lookup tables to account for different wavelengths



Same algorithm on both platforms?

- Apply C6-like thresholds for cloud masking, pixel selection and aggregation
- Run "MODIS-like" algorithm on both M-IFF and V-IFF data

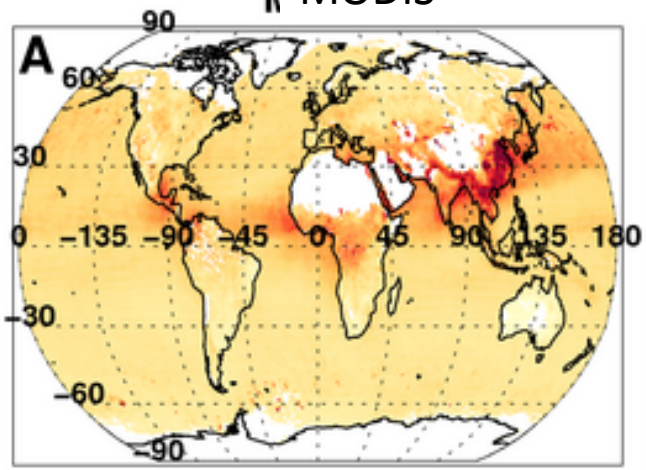


→ Much more similar AOD structure

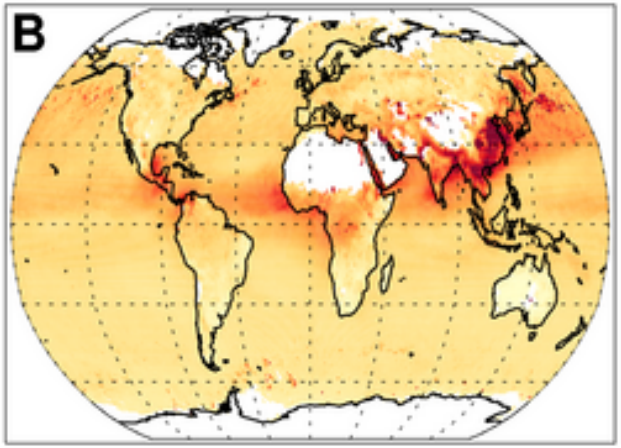
→ Still differences in coverage and magnitude. We are learning why. (Cloud masking/spatial variability thresholds?)

Gridded seasonal AOD (Spring 2013)

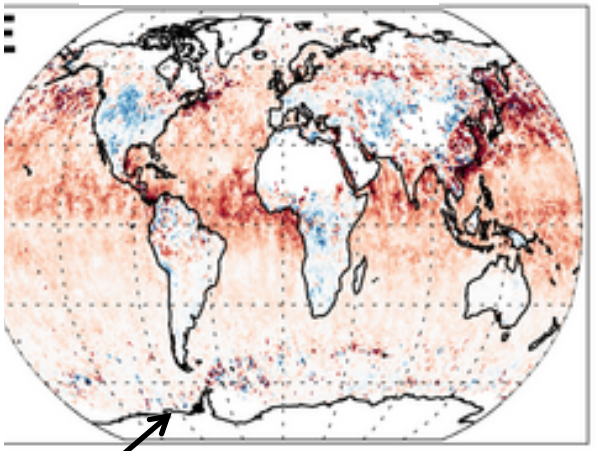
MODIS



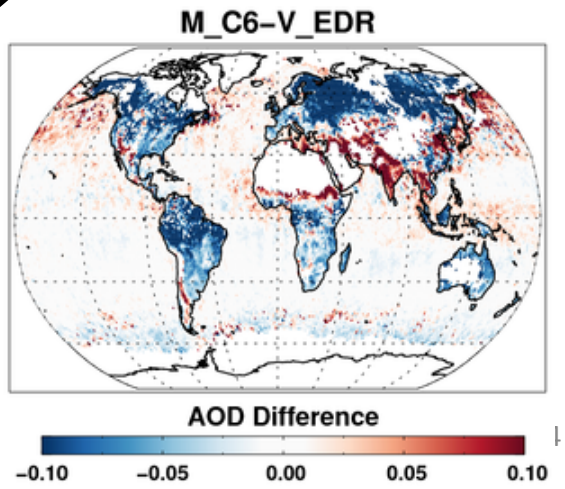
MODIS-like on VIIRS



Difference M - V



Versus…



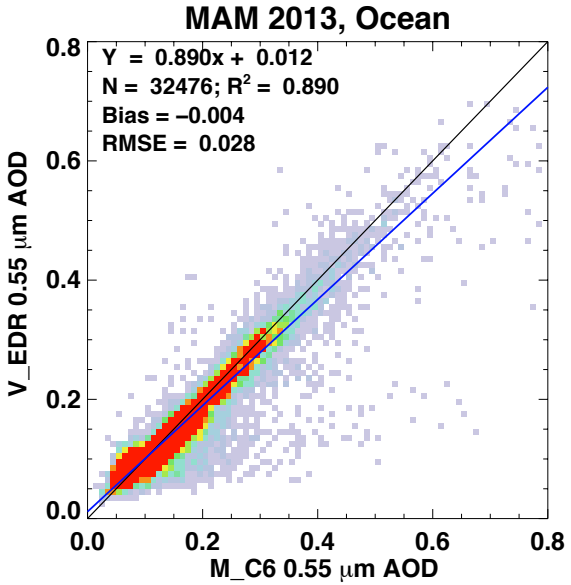
Running MODIS-like on VIIRS has reduced global AOD differences and has similar global sampling

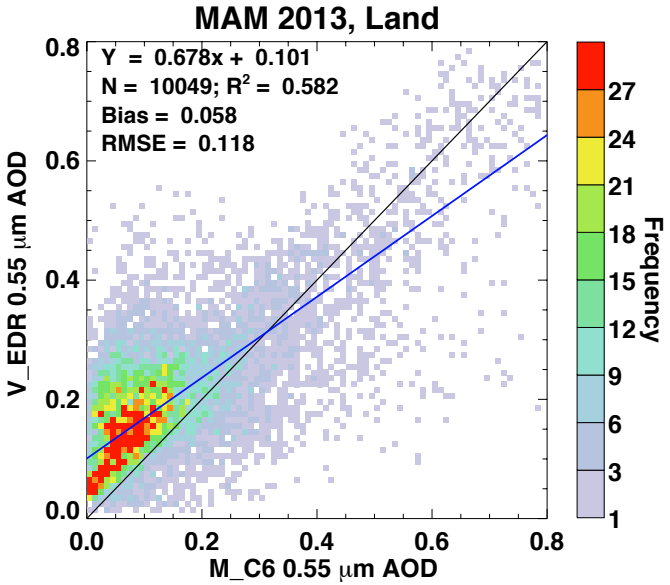
Systematic bias over ocean (VIIRS high by 15%)

Not systematic bias over land (MODIS high by 5%)

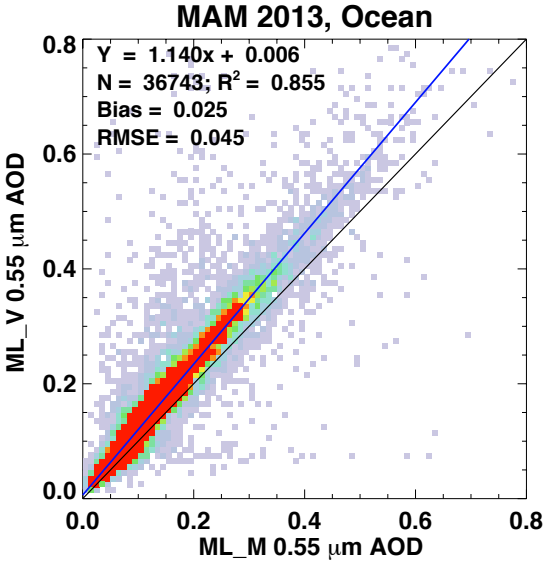
Comparing gridded AOD (Spring 2013)

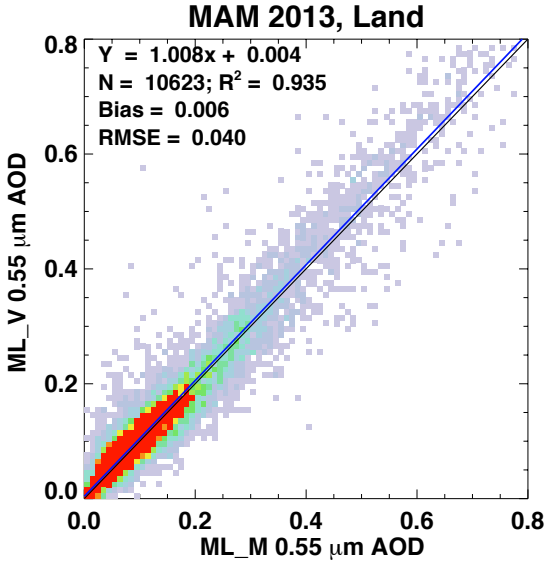
VIIRS_EDR vs MODIS





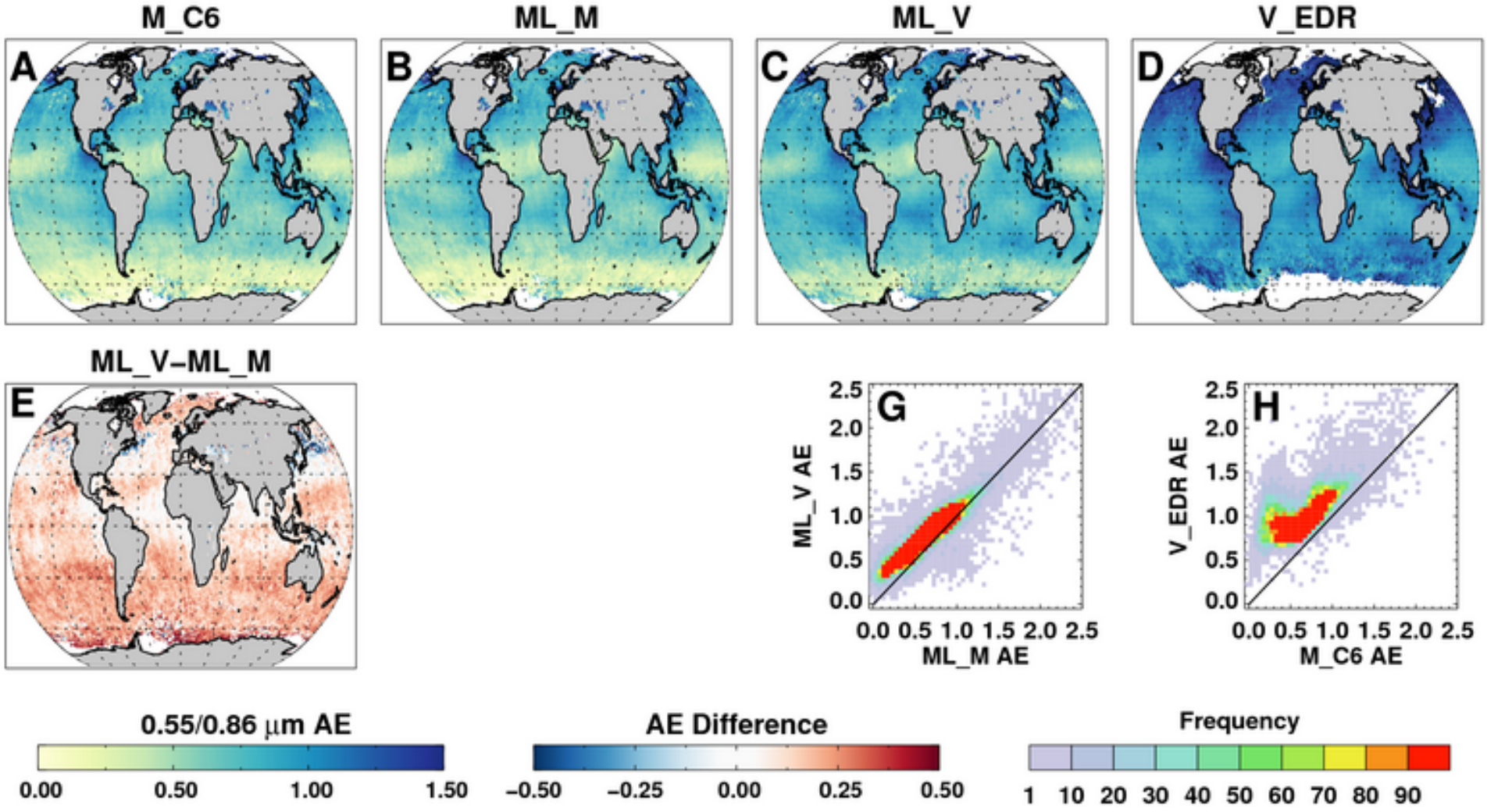
MODIS-like (VIIRS) vs MODIS



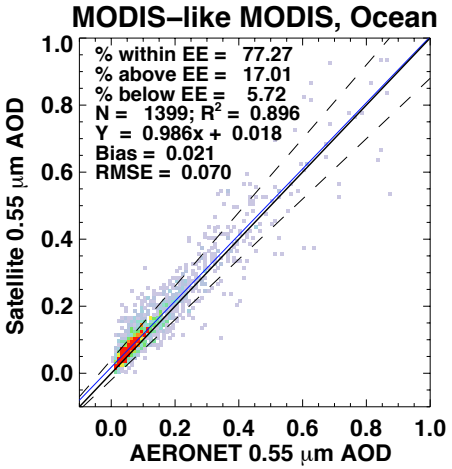


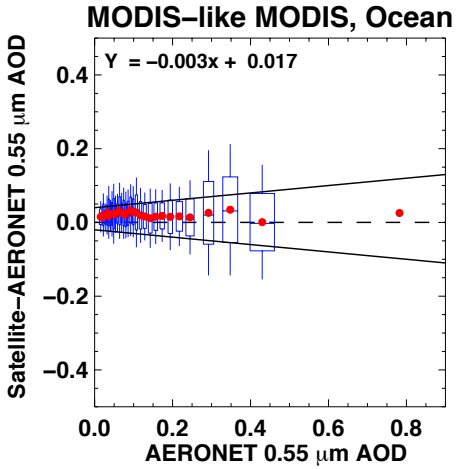
New data
More like MODIS
But 1.15 slope over ocean!

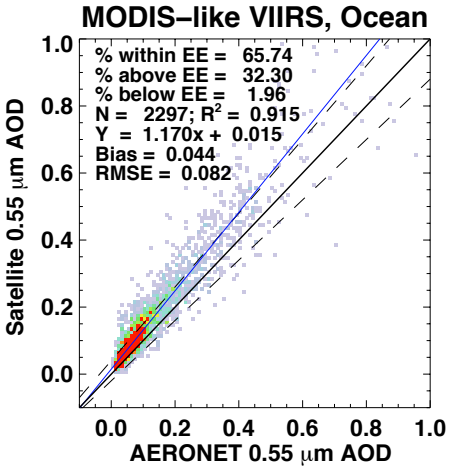
Angstrom Exponent

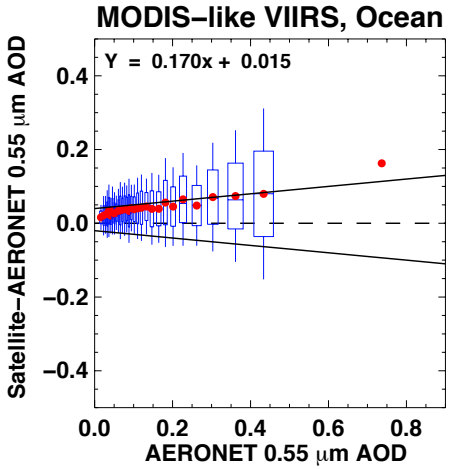


MODIS-like on VIIRS has Angstrom Exponent that looks much more like MODIS







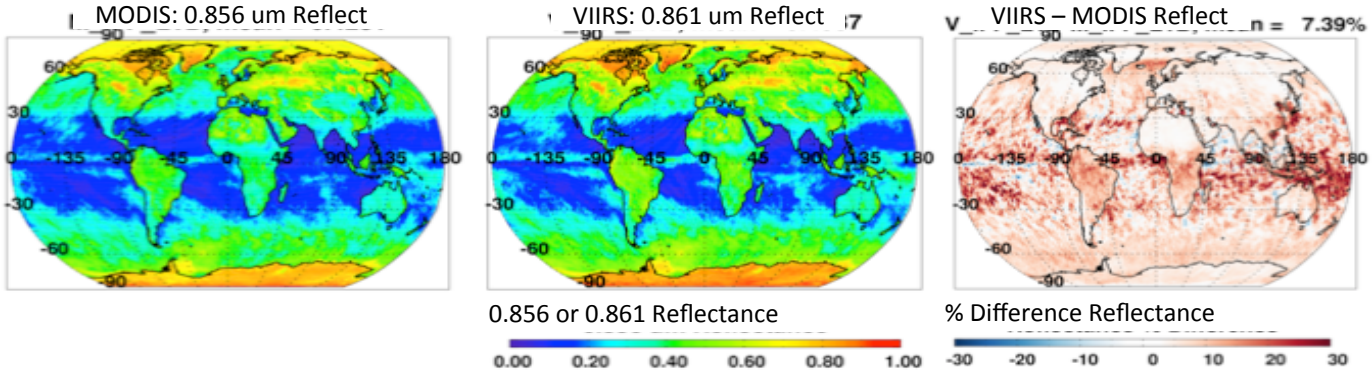


Comparing to AERONET and calibration

MODIS-like on VIIRS has great correlation but 1.17 slope!

Studies such as Uprety et al., (2013) do radiometric comparisons between VIIRS and MODIS and find that VIIRS may be 2% high in some bands.

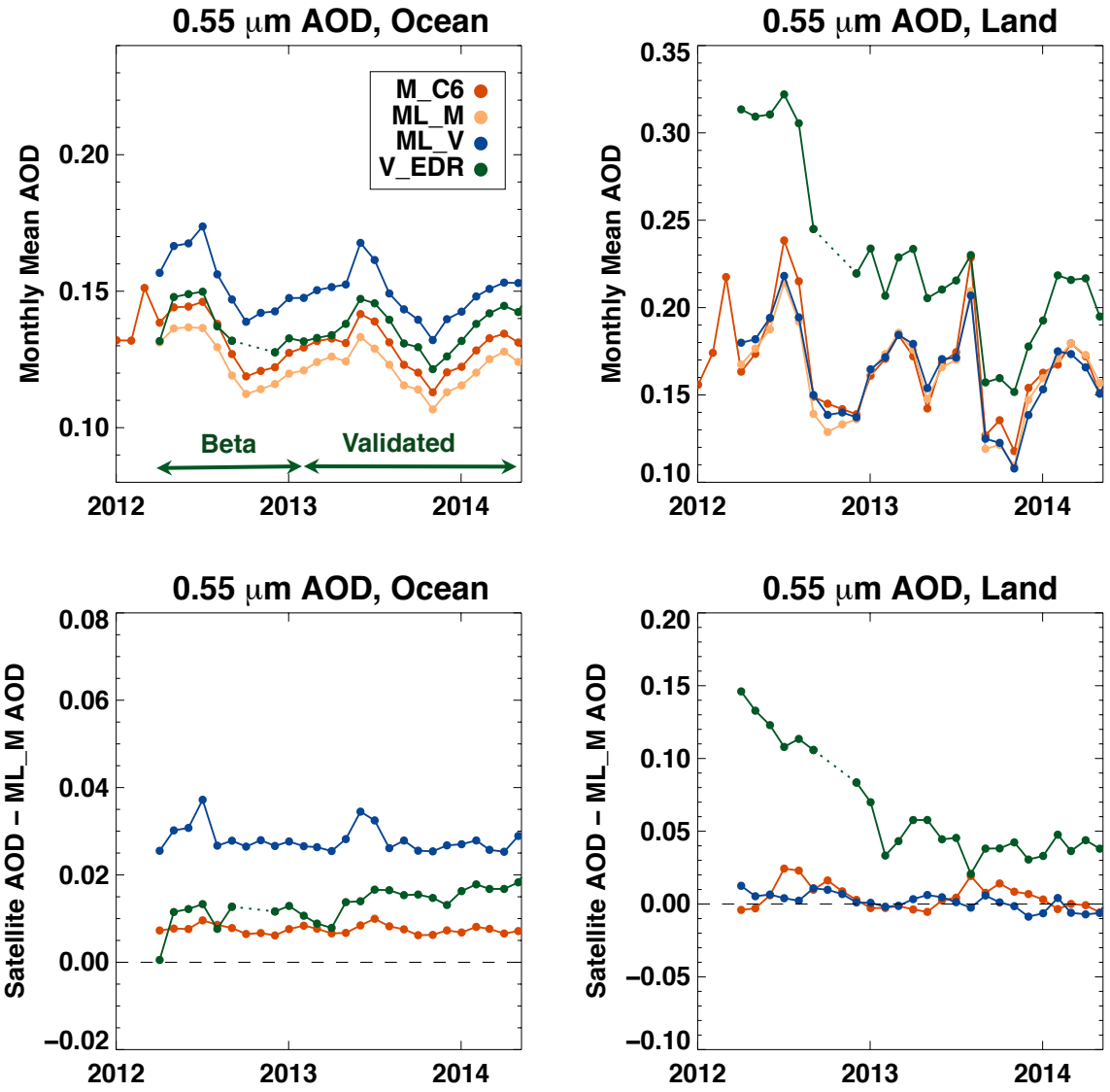
2% high bias is sufficient to give a 1.17 slope over ocean without the adding same bias to land.



Will VIIRS continue MODIS? How would we know?

- Convergence of gridded (Level 3 –like) data?
  - For a day? A month? A season?
  - What % of grid boxes must be different by less than X?
    - in AOD? In Angstrom Exponent?
- What about "sampling"?
  - Even if the mean, histograms and gridded data looked similar, what about the "retrievability?"
  - Fraction of retrieved pixels / total pixel
- Comparison (validation) with AERONET?

A time series (of sorts) so far

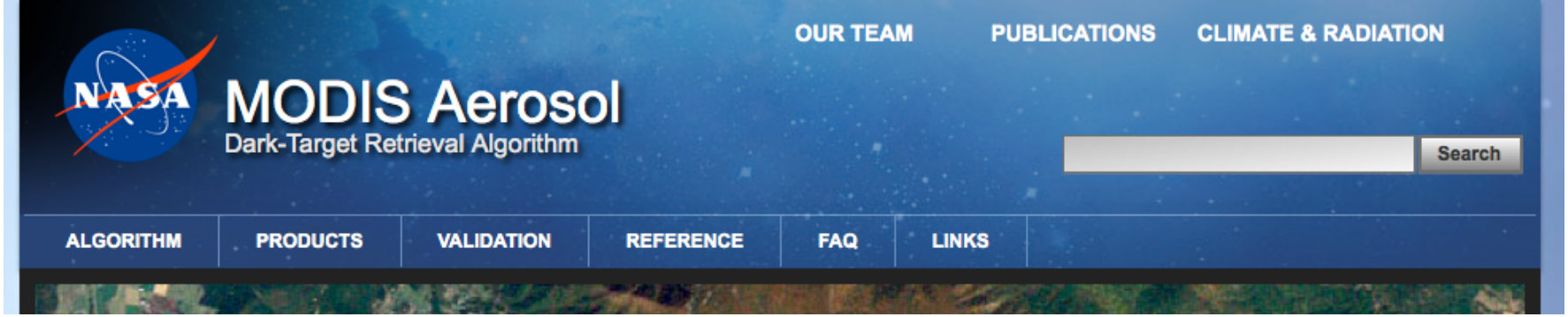


Summary (VIIRS)

- MODIS-DT Collection 6 –
  - Aqua/Terra level 2, 3 available now;
  - Extended diagnostics, DT/DB merge, science improvements
  - "Trending" issues reduced, but 15% Terra/Aqua offset remains (suspect calibration).
- VIIRS-IDPS (MODIS-ish over ocean; not over land)
  - VIIRS is "similar" instrument, yet different then MODIS
  - The NOAA product has similar global EE to MODIS (over ocean).
  - With 50% wider swath, VIIRS has daily coverage
- VIIRS-DT – funded, in development,
  - Ensures *algorithm* consistency with MODIS DT.
  - IFF-based granules are being processed now (we can share)
  - 20% NPP/Aqua offset over ocean (suspect calibration).
- Routine NASA-VIIRS products will be processed by U Wisconsin.
  - Move from IFF-based to yet-undecided formats
  - MODIS-VIIRS Science Team meeting next week.
  - Discussion on how to move forward?

Summary (VIIRS-cont)

- Can VIIRS continue the MODIS record?
  - We believe we need to apply the same algorithm
  - Calibration is a concern.
- We still need to define "how similar is good enough"?
- Which statistics must converge?
  - Expected error (validation)
  - Sampling
  - Means/variance
  - At 0.55 μm only? At other wavelengths?
  - Etc
- Keep open discussion with our "super-users" including CERES team.



- Web site in development/ATBDs being updated
- Reference for all things "dark target"
  - The algorithms and assumptions
  - Examples
  - Validation
  - Primary publications
  - Educational material
  - FAQ
  - Links to data access
  - Considering a "forum"

http://darktarget.gsfc.nasa.gov